

# **Real Time Energy Reconstruction in the ATLAS Hadronic Tile Calorimeter and ATLAS sensitivity to Extra Dimension Models**

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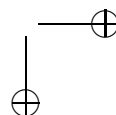
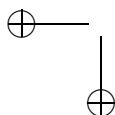
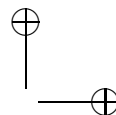
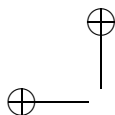


A dissertation submitted to the Universitat de Valencia  
for the degree of Doctor of Philosophy

## Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

Belén Salvachúa Ferrando





## Prefacio

Este trabajo ha sido realizado dentro del marco de la colaboración ATLAS. Aquí se presentan dos estudios, ambos relacionados con el detector ATLAS y su funcionamiento.

La reconstrucción en tiempo real de la energía que se ha depositado en las celdas de los calorímetros del detector ATLAS es de crucial importancia para poder desarrollar algoritmos eficientes de segundo nivel de selección de sucesos. Aquí presento un estudio sobre el rendimiento y la implementación del algoritmo *Optimal Filtering*, que es capaz de reconstruir a partir de la señal digitalizada del calorímetro de tejas TileCal de ATLAS la energía depositada en sus celdas y el tiempo de llegada de la señal, así como un factor de calidad de la reconstrucción. También se presenta la implementación y el funcionamiento de *Optimal Filtering* en los procesadores de señal digital instalados en los *Read-Out Drivers* (ROD) de TileCal. De esta manera, los RODs son capaces de proporcionar al segundo nivel de selección de ATLAS la información requerida para el filtrado de eventos. En este trabajo también se describe el formato de salida elegido para el codificado de las variables reconstruidas en el ROD. Este formato se ha creado cumpliendo los requisitos del formato de salida general de ATLAS.

Por otra parte, la principal motivación del experimento ATLAS es la búsqueda del boson Higgs y el estudio de física más allá del Modelo Estándar. La segunda

parte de la tesis presenta la búsqueda de resonancias del gluón predichas por modelos que incorporan dimensiones espaciales adicionales. La búsqueda de gluones excitados en este trabajo se investiga a través de sus desintegraciones hadrónicas a jets de alto momento transversal ( $p_T$ ), medido en el calorímetro TileCal. Para completar este estudio se investiga también la polarización del quark top como observable para poder discernir entre diferentes modelos que predicen una resonancia pesada con estado final similar.

La descripción general del detector ATLAS se encuentra en el capítulo 1. ATLAS está formado por varios subdetectores. La parte más interna contiene el detector de trazas o *Inner*, cuyas funciones son la identificación de electrones, el etiquetado de leptones  $\tau$  y b-quarks, la reconstrucción de vértices secundarios y la reconstrucción del momento transversal con una precisión del 30 % para  $p_T = 500$  GeV. El detector *Inner* está dentro de un solenoide que proporciona un campo magnético de 2 T que permite curvar en el plano transversal al haz las partículas cargadas que atraviesan el detector y así medir su momento transversal con la precisión requerida. ATLAS está también equipado con calorímetros electromagnético y hadrónico, con una resolución energética de  $10 \text{ \%}/\sqrt{E} \oplus 0.7 \text{ \%}$  para el electromagnético y  $50 \text{ \%}/\sqrt{E} \oplus 3 \text{ \%}$  para los barriles y tapones hadrónicos y  $100 \text{ \%}/\sqrt{E} \oplus 10 \text{ \%}$  para los calorímetros *forward*. Finalmente, ATLAS está rodeado por un espectrómetro de muones con una resolución de 10 % para  $p_T = 1$  TeV, la curvatura de estos muones la proporciona un campo magnético toroidal con una potencia de curvatura de entre 3-8 Tm.

El capítulo 2 empieza con una descripción detallada del calorímetro hadrónico TileCal. Este calorímetro está compuesto por un barril central y dos barriles laterales, los tres barriles están segmentados azimutalmente en 64 módulos. TileCal es un calorímetro de muestreo, con tejas de plástico centelleador como material activo y hierro como material pasivo. La luz generada en las tejas centelleadoras se recoge con fibras ópticas (WLS) que cambian la longitud de onda de la luz transmitida y la conducen a los fotomultiplicadores. Las celdas de lectura se definen al agrupar varias fibras al mismo fotomultiplicador creando una estructura proyectiva en pseudorapidez. El pulso generado en el fotomultiplicador se amplifica y acomoda a la electrónica de digitalización, que toma muestras de la señal

cada 25 ns. Cuando se selecciona un evento estas muestras se envían a través de fibra óptica a los *Read-Out Drivers*. Los RODs son unas tarjetas que leen la información generada en el calorímetro, la procesan y la envían a la cadena general de adquisición de datos de ATLAS. Para procesar la información del calorímetro los RODs están dotados de unidades de procesamiento que contienen FPGAs (*Field Programmable Gate Array*) y procesadores de señal digital (DSP). El algoritmo *Optimal Filtering*, descrito en este trabajo, está implementado en los DSP del ROD, mientras que los FPGA realizan tareas de sincronización y control de calidad de los datos. El capítulo 2 termina con la descripción de los DSP usados en los RODs y de la configuración usada durante los tests del calorímetro con haces de partículas y con muones cósmicos.

El algoritmo *Optimal Filtering* calcula la energía depositada en el calorímetro y el tiempo de llegada de la señal como la suma ponderada de las muestras de la señal digitalizada. El capítulo 3 describe el funcionamiento y desarrollo del algoritmo *Optimal Filtering* y el procedimiento para calcular los pesos o ponderaciones. *Optimal Filtering* se ha desarrollado adaptándolo a las condiciones del LHC, donde los datos están sincronizados con el reloj de digitalización, sin embargo, durante las fases de test con haces de partículas y con muones cósmicos la adquisición no está sincronizada con la digitalización. En el capítulo 3 se presenta la incorporación de un método iterativo para solucionar este problema y termina con la descripción de la implementación de *Optimal Filtering* en los DSP del ROD y con la propuesta de un formato de datos para empaquetar la energía, fase y factor de calidad reconstruidos *online* y enviarlo a la adquisición general de ATLAS.

El capítulo 4 contiene una introducción al Modelo Estándar. Esta teoría describe las interacciones entre partículas elementales a través del intercambio de partículas intermedias. Así pues, la materia está constituida por fermiones (partículas de espín  $\frac{1}{2}$ ) y las partículas intermedias son bosones (con espín entero). El Modelo Estándar es una teoría *gauge*, lo que significa que los Lagrangianos de las interacciones electromagnética, débil y fuerte son invariantes bajo transformaciones locales *gauge*. Sin embargo, para introducir la masa de las partículas se necesita un nuevo mecanismo, el mecanismo de *Higgs* o rotura espontánea de la simetría. A través de este mecanismo los fermiones adquieren

masa y aparece una nueva partícula, el bosón de *Higgs*, que se espera ser descubierta en el LHC. Aunque el Modelo Estándar explica la mayor parte de los datos recogidos con experimentos de física de altas energías, todavía hay algunos aspectos como las oscilaciones de neutrinos descubiertas recientemente y el problema de la jerarquía que indican que esta teoría está incompleta. Otros modelos, como Supersimetría, *Little Higgs* o Dimensiones Extra intentan resolver estos problemas. En el capítulo 4 se presenta una breve descripción de estos modelos.

En el capítulo 5 se presenta la búsqueda de resonancias del gluón en el detector ATLAS predichas por modelos con dimensiones adicionales. La búsqueda se estudia a través de las desintegraciones hadrónicas del gluón excitado, en particular a quark-antiquark *beauty* y quark-antiquark *top* para diferentes masas del gluón excitado comenzando por 1 TeV. Se presenta también el estudio de la contribución del ruido y se estima la sensibilidad del detector ATLAS a poder observar las resonancias del gluón. En la segunda parte del capítulo 5 se estudia la polarización del quark *top* cuando este proviene de la desintegración de resonancias pesadas. Varios modelos predicen este estado final, sin embargo, la polarización del quark *top* es sensible a los acoplos de la teoría investigada. Si la señal puede ser extraída del ruido y observada en el LHC, la polarización del quark *top* se podría medir y usar como parámetro para discriminar entre diferentes modelos.

La tesis termina con un apartado sobre las principales conclusiones de este trabajo. Por una parte se ha llevado a cabo la implementación del algoritmo *Optimal Filtering* en los DSPs de los RODs del calorímetro TileCal y se han tomado datos con muones cósmicos como fuente para la validación de dicho algoritmo. Por otra parte se presenta la sensibilidad del detector ATLAS a observar señales predichas por teorías que incorporan dimensiones adicionales.

Belén Salvachúa Ferrando  
Valencia, Octubre 2007

## Preface

This work has been fulfilled within the ATLAS collaboration. I present here two studies, both related with the ATLAS detector and its operation.

The ATLAS detector is described in chapter 1 whereas chapter 2 shows an introduction to the ATLAS tile calorimeter and the TileCal Read-Out Drivers (ROD) where the first part of the thesis is developed. In chapter 3 I present the study and the implementation of the Optimal Filtering algorithm in the TileCal Read-Out Drivers. The ROD provides the energy and the arrival time of the digital signal that is generated in the tile calorimeter. These parameters are reconstructed online using the Optimal Filtering algorithm, the RODs also provide a quality factor of the reconstruction. This information is sent to the standard ATLAS acquisition data flow with a specific data format defined in this thesis.

Chapter 4 contains a short introduction to the Standard Model, presents its problems and describes other theories like Supersymmetry, Little Higgs or Extra Dimension models that try to solve them. The ATLAS experiment is enhanced to detect the Higgs boson and to study the physics at the TeV scale. Chapter 5 shows the study of the Kaluza-Klein gluon resonances predicted by models with extra dimensions. These searches are investigated through the decays of the excited gluons to high transverse momentum jets ( $p_T$ ) measured in the tile calorimeter. In this chapter I also propose the measurement of the polarization of the top quark

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from the excited gluon decay to discriminate between different models with similar final signatures.

A summary and the main conclusions of the analyses are presented in the last part of the thesis. On one hand the implementation of the Optimal Filtering algorithm in the ROD DSPs of TileCal and the validation of this algorithm using cosmic muons from the ATLAS commissioning has been done. And on the other hand the ATLAS sensitivity to observe signatures predicted by extra dimension models has been presented.

Belén Salvachúa Ferrando  
Valencia, October 2007

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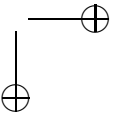
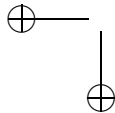
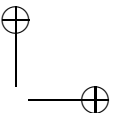
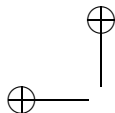
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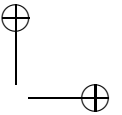
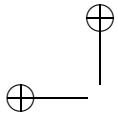
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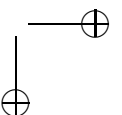
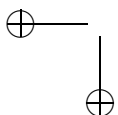
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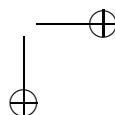
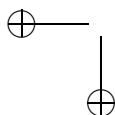
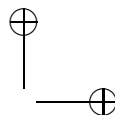
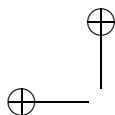




*“Writing in English is the most ingenious torture  
ever devised for sins committed in previous lives.”*

— James Joyce





## Chapter 1

# LHC and ATLAS

*“There are two possible outcomes: if the result confirms the hypothesis, then you’ve made a measurement. If the result is contrary to the hypothesis, then you’ve made a discovery.”*

— Enrico Fermi, 1901 – 1954

## 1.1 The Large Hadron Collider

### 1.1.1 The machine

The Large Hadron Collider (LHC) [1] is being built at CERN inside the 27 km long tunnel used formerly by LEP [2]. The main goal of the LHC project is the discovery of the Higgs boson and the study of new physics at the 1 TeV scale. In order to achieve these goals the LHC should provide higher luminosities and energies than previous accelerators. The LHC is designed to achieve proton-proton collisions with a center of mass energy of 14 TeV and luminosity up to  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ .

Since protons are composite particles, the hard collisions involve their elementary constituents, the partons. For this reason, the effective energy that can be reached in a hard collision is  $\sqrt{x_1 x_2 s}$ ,  $x_1$  and  $x_2$  being the momentum fraction of the two colliding partons and  $\sqrt{s}$  the center of mass energy of the protons. Therefore, the effective center of mass energy may be much smaller than the nominal center of mass energy.

The luminosity is the factor relating the interaction cross section  $\sigma_{\text{int}}$  for a given process and the corresponding event rate  $R$ ,

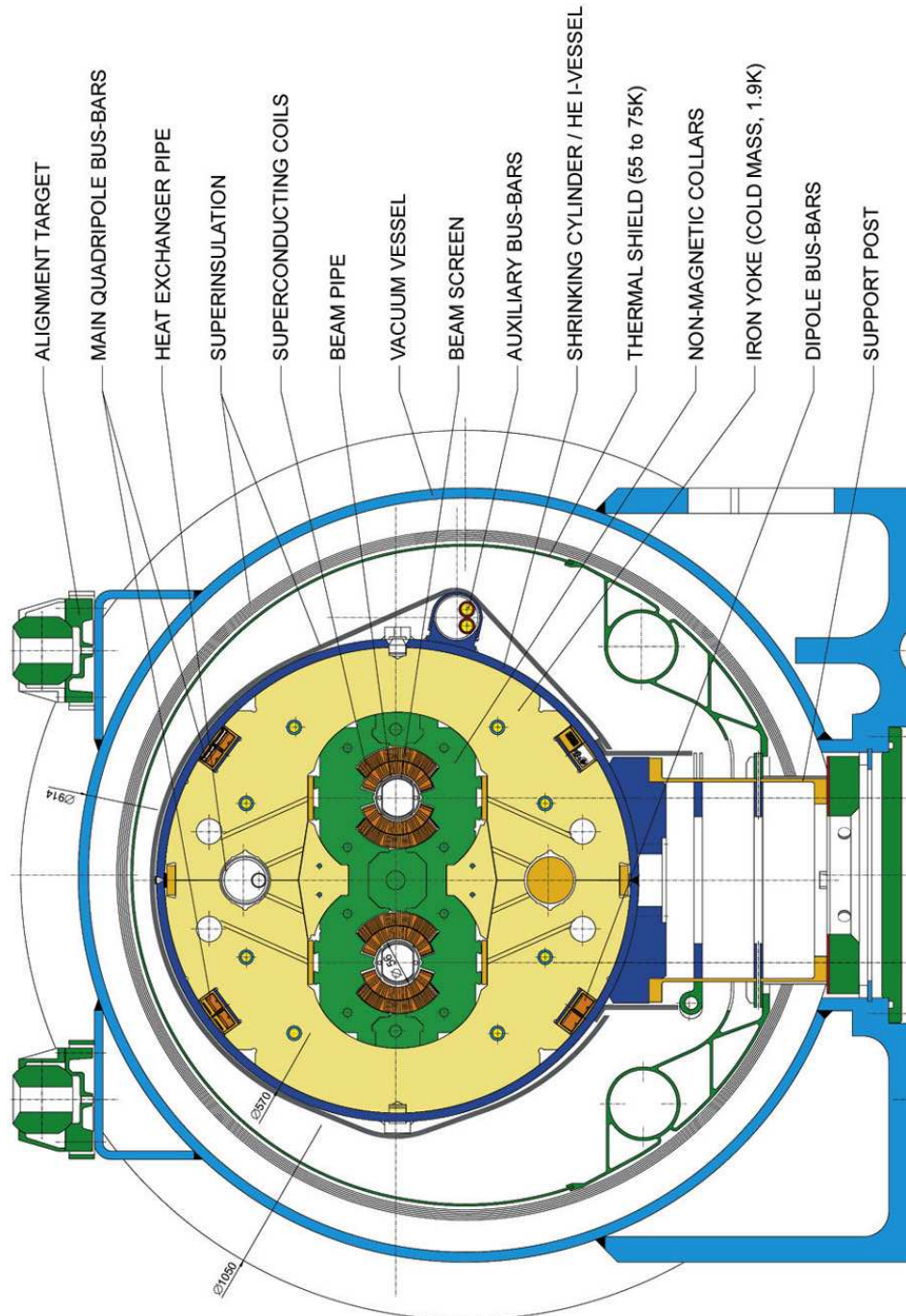
$$R = \mathcal{L} \sigma_{\text{int}} , \quad (1.1)$$

and depends only on machine parameters:

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F , \quad (1.2)$$

where the number of particles per bunch is  $N_b$ , the number of bunches per beam is  $n_b$ , the revolution frequency is  $f_{\text{rev}}$ , the transverse normalized emittance is  $\epsilon_n$ , the amplitude function at the interaction point is  $\beta^*$ ,  $F$  is a reduction factor due to the crossing angle at the interaction point, and finally  $\gamma_r$  is the relativistic gamma factor (see Table 1.1). Therefore, the nominal peak luminosity obtained with the LHC parameters is  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . The estimated operation time is around 30% thus the integrated luminosity of 1 year running with nominal parameters is around  $100 \text{ fb}^{-1}$ . A first period with not so ambitious luminosity is also foreseen with an integrated luminosity of around  $10 \text{ fb}^{-1}$  for 1 year. This is called low luminosity period and the drop of the luminosity is mainly due to the smaller number of particles per bunch which is expected to be  $0.4 \times 10^{11}$ . High luminosities require intense beams, excluding the use of anti-protons. For this reason, the LHC is a proton-proton collider, unlike former hadron colliders like the CERN SPS or the Fermilab Tevatron. Intense multi-bunch beams also require separate vacuum pipes and magnetic fields for each beam, with common sections only at injection and in the interaction regions. Inside the LEP tunnel, there is not enough space for two separate rings. As a result, twin magnets inside the same mechanical structure and cryostat have been designed for the LHC, as shown in Figure 1.1.





**Figure 1.1:** Diagram showing the cross-section of a Large Hadron Collider (LHC) dipole magnet.

**Table 1.1:** LHC beam parameters.

|                                              | <b>Injection</b>                         | <b>Collision</b>                         |
|----------------------------------------------|------------------------------------------|------------------------------------------|
| Proton energy                                | 450 GeV                                  | 7000 GeV                                 |
| Relativistic gamma $\gamma_r$                | 479.6                                    | 7461                                     |
| Number of particles per bunch $N_b$          | $1.15 \times 10^{11}$                    | $1.15 \times 10^{11}$                    |
| Number of bunches $n_b$                      | 2808                                     | 2808                                     |
| RMS bunch length                             | 11.24 cm                                 | 7.55 cm                                  |
| Amplitude function $\beta^*$                 | —                                        | 0.55 m                                   |
| Transverse normalized emittance $\epsilon_n$ | 3.5 $\mu\text{m rad}$                    | 3.75 $\mu\text{m rad}$                   |
| Reduction factor $F$                         | —                                        | 0.836                                    |
| Peak luminosity                              | $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ | $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ |
| Inelastic cross section                      | —                                        | 60 mb                                    |
| Total cross section                          | —                                        | 100 mb                                   |
| Revolution frequency $f_{\text{rev}}$        | 11.245 kHz                               | 11.245 kHz                               |
| Bunch frequency                              | 40.08 MHz                                | 40.08 MHz                                |

The beams circulate inside vacuum pipes, to avoid undesirable collisions with gas molecules. The most challenging part of the LHC project is the construction of 1232 superconducting (1.9 K) dipole magnets to keep the beams in orbit around the 27 km circumference. These 14 m long dipole magnets should provide a uniform magnetic field of 8.4 T, sustaining currents of 11.7 A. A liquid-helium cryogenic system is needed to keep the magnets cold at 1.9 K.

### 1.1.2 The experiments

Five detectors have been designed to exploit the physics at the LHC. Two general-purpose experiments, ATLAS (A Toroidal LHC Apparatus) [3] and CMS (Compact Muon Solenoid) [4], are optimized to study new physics at the TeV scale. A detailed description of the ATLAS detector is found in section 1.2. LHCb (Large Hadron Collider Beauty) [5] and TOTEM (Total Cross Section, Elastic Scattering and Diffraction Dissociation) [6] are dedicated experiments, the first to investigate B-physics and the second to measure the total proton-proton cross

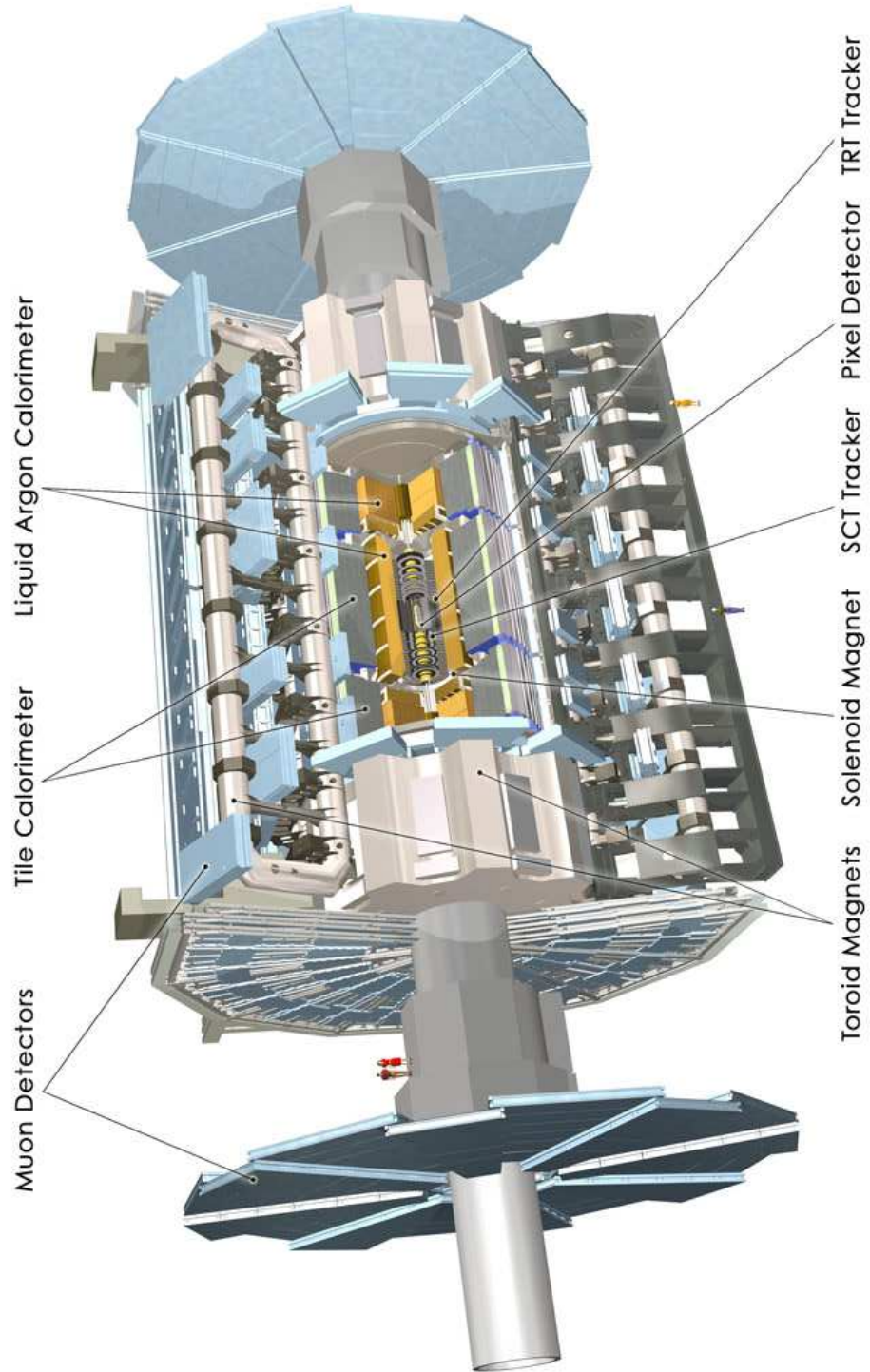
section at the LHC. An additional experiment called ALICE (A Large Ion Collider Experiment) [7] has been proposed to study Pb-Pb collisions.

## 1.2 The ATLAS Detector

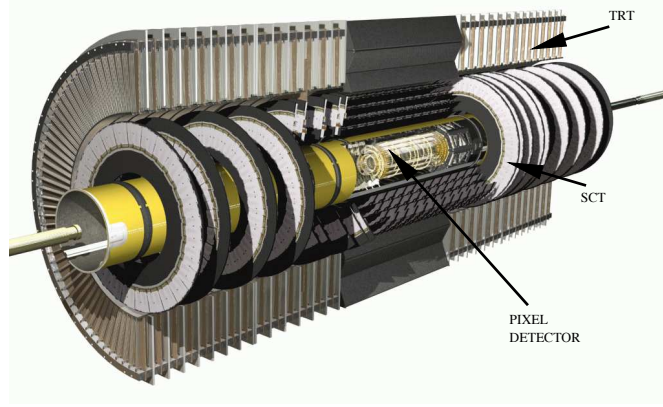
### 1.2.1 Overall layout

The ATLAS detector [3] is a general purpose detector designed to exploit the full discovery potential of the LHC. Since the main goal of the LHC is the discovery of the Higgs boson or new unexpected physics, ATLAS should be sensitive to a large variety of final-state signatures. Therefore, the design is optimized to achieve very good electron and photon identification, good measurements of jets and missing transverse energy ( $E_T^{\text{miss}}$ ), good tracking efficiency, large acceptance in  $\eta$  and capability for triggering events containing particles at high  $p_T$ .

The detector is composed by several subsystems, each one with specific characteristics according to its functionality (see Figure 1.2). The main purpose of the inner detector is to reconstruct tracks with a track momentum resolution of 30% at  $p_T = 500$  GeV which will be used for tagging of b-quarks and  $\tau$ -leptons, secondary vertex reconstruction and lepton identification. In order to bend the tracks from charged particles, the inner detector is inserted inside a cylindrical magnet with 5.3 m length and 1.22 m inner radius, providing a solenoidal magnetic field of 2 T. ATLAS is also equipped with electromagnetic (EM) and hadronic (HAD) calorimeters, with expected resolution of  $10\%/\sqrt{E} \oplus 0.7\%$  for the EM and  $50\%/\sqrt{E} \oplus 3\%$  for the barrel and end-cap HAD, and  $100\%/\sqrt{E} \oplus 10\%$  for the forward hadronic calorimeter. Finally, a muon spectrometer with resolution of 10% at  $p_T = 1$  TeV surrounds the whole detector. A more detailed description of the various subsystems is provided in the following sections.



**Figure 1.2:** Overall layout of the ATLAS detector.



**Figure 1.3:** Simulated view of the ATLAS inner detector (from the GEANT program).

### 1.2.2 Inner Detector

The main goal of the inner detector [8] is to track charged particles from the interaction point up to the electromagnetic calorimeter. The design combines two different techniques, high resolution spatial measurements for the inner part, provided by pixel and micro-strip detectors, and continuous tracking in the outer part, using a transition radiation detector. These sub-detectors operate inside a solenoidal magnet with central field of 2 T to ensure the measurement of charged particle momenta. Figure 1.3 shows a drawing of the ATLAS inner detector.

The pixel detector is composed by three barrel layers and six end-cap disks. The first layer (B-layer) covers the pseudo-rapidity range  $|\eta| < 2.5$  and is placed at a distance of 5 cm from the interaction point. This layer plays a very important role in b-tagging studies. The second and third barrel layers cover the pseudo-rapidity range  $|\eta| < 1.7$  and are located at 11 cm and 15 cm, respectively, from the interaction point. The end-cap disks provide additional coverage in the pseudo-rapidity range  $1.7 < |\eta| < 2.5$ . All layers are instrumented with silicon diode detectors, segmented in small rectangles or pixels of  $50 \times 400 \mu\text{m}^2$ . Particles traversing the silicon pixels deposit a small fraction of energy ( $\sim \text{eV}$ ) and generate electron-hole pairs drifting to a segmented readout plane. A discriminator located in the read-

out chip converts the analog signal into one bit per channel (hit/no hit), reducing in this way the total amount of data generated by the  $\sim 100$  million channels.

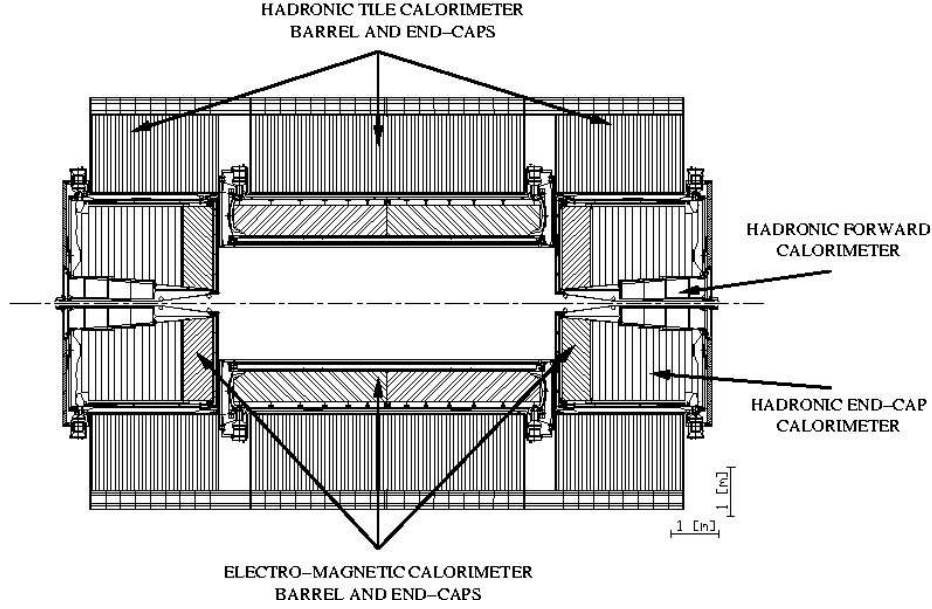
The Semi-Conductor Tracker (SCT), or micro-strip detector, is placed at 30 cm from the interaction point, between the pixel and the transition radiation detector. It is composed by four precision central barrels and two end-caps of 9 wheels each. The central barrel covers a pseudo-rapidity range of  $|\eta| < 1.4$  and the end-cap wheels extend this range up to  $|\eta| < 2.5$ . The readout is segmented into silicon micro-strips. Single sided silicon micro-strips provide just one hit coordinate. In order to get an additional coordinate, two single sided detectors are glued back-to-back with a stereo angle of 40 mrad. The third coordinate is provided by the detector position itself.

The Transition Radiation Tracker (TRT) is located at 56 cm from the interaction point, between the SCT and the electro-magnetic calorimeter. The barrel part covers the pseudo-rapidity range  $|\eta| < 0.7$  and the end-caps extend the range up to  $|\eta| < 2.5$ . It is composed by straw tubes. The inner surface of the straws is covered by aluminum and acts as a cathode. A gold-plated tungsten wire in the middle of the straw is the anode. The straws are filled with a gas mixture of xenon, carbon fluoride and carbon dioxide in proportion 70:20:10. This system detects the gas ionization produced by particles and the X-rays from the transition radiation. This transition radiation is produced when a relativistic particle traverses an inhomogeneous like medium and allows particle identification.

Using the information of the three sub-systems, the inner detector provides at least 7 space points (3 from the pixel and 4 from the SCT) and roughly 36 measurements in the TRT. This information is used to calculate the momentum and the impact parameter of charged tracks.

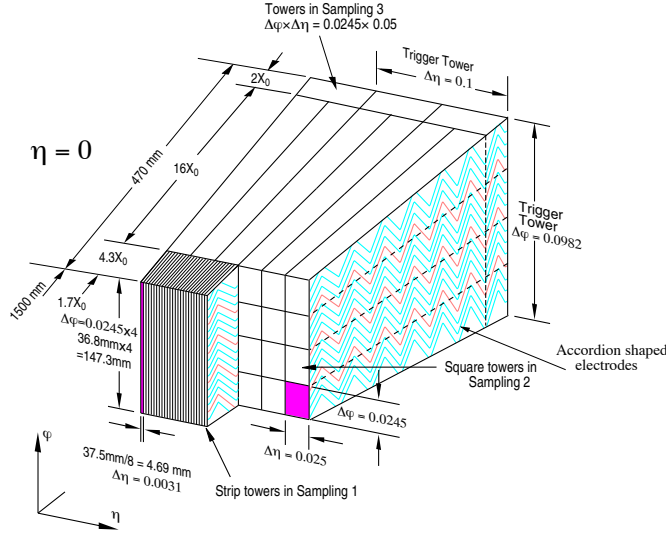
### 1.2.3 Calorimetry

The design of ATLAS calorimetry is optimized to detect Higgs boson decays. In particular, the calorimeters are sensitive to  $H \rightarrow \gamma\gamma$  for  $m_H < 130$  GeV,



**Figure 1.4:** Two dimensional view of the ATLAS calorimeter layout.

$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  for  $130 \text{ GeV} < m_H < 600 \text{ GeV}$  and  $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$  and  $H \rightarrow WW \rightarrow \ell\nu jj$  for  $m_H > 600 \text{ GeV}$ . For this reason the ATLAS calorimeters should be able to measure with high precision the energy and position of electrons and photons, the energy and direction of jets, the missing transverse momentum of the event, to separate electrons and photons from hadrons and jets, and  $\tau$  hadronic decays from jets as well. Additionally, they should provide event discrimination at the trigger level. Since the center of mass energy is 14 TeV, the energy spectrum of the generated particles is very wide, and the calorimeters should provide good energy resolution from energies of a few GeV up to a few TeV. At high luminosity ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ), 19 soft collisions are generated every 25 ns. Therefore the response of the detector should be fast enough ( $< 50 \text{ ns}$ ) to process pile-up events. Moreover, the ATLAS calorimeters should be radiation hard and survive at least 10 years of operation. Figure 1.4 shows a two dimensional view of the ATLAS calorimeter layout.



**Figure 1.5:** Sketch of the readout granularity of the ATLAS barrel electro-magnetic calorimeter with accordion-shaped electrodes.

## Electromagnetic Calorimetry

The ATLAS electromagnetic calorimetry [9] is based on lead-liquid-argon detectors with accordion-shaped kapton electrodes and absorber plates (see Figure 1.5). It is composed by a central barrel covering a pseudo-rapidity range  $|\eta| < 1.475$  and two end-caps covering  $1.375 < |\eta| < 3.2$ . The EM barrel is divided into two equal cylinders of inner radius 1.15 m and outer radius 2.25 m, separated by a small gap ( $\sim$  mm) at  $z = 0$ . Each end-cap is formed by two coaxial wheels, the inner covering  $1.375 < |\eta| < 2.5$  and the outer  $2.5 < |\eta| < 3.2$ .

In the region of high precision physics ( $|\eta| < 2.5$ ) the calorimeter is longitudinally segmented into 3 sampling regions allowing good particle identification. For  $|\eta| > 2.5$  just 2 samplings are available. The transverse granularity of the detector varies with  $\eta$  but it is always kept below  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . In order to minimize effects on the energy resolution from longitudinal fluctuations of high energy showers ( $E > 500$  GeV), the total thickness of the EM calorimeter is 24 radiation lengths for the barrel and 26 for the end-caps.



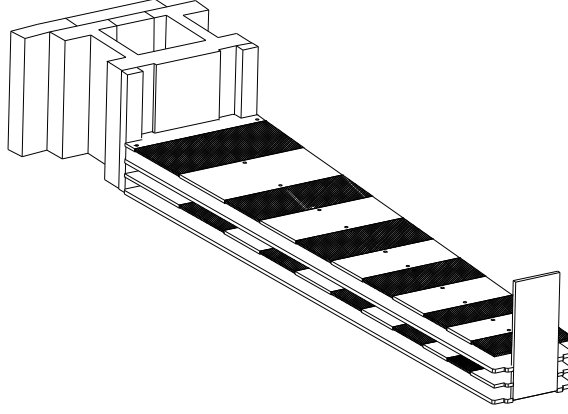
The barrel is inserted into a cryostat surrounding the ATLAS inner detector. The two end-caps are inserted into two additional cryostats, together with the hadronic end-cap and the forward LAr calorimeters. A presampler detector, made of an active layer of liquid-argon, is placed behind the cryostat cold wall to correct for the energy lost by electrons and photons in the dead material. In the region between the barrel and the end-caps, the presampler is complemented by a scintillator situated between the barrel and the end-cap cryostats.

The analog signal is readout by preamplifiers located outside the cryostats. The output is formed by bipolar shapers, sampling the signal every 25 ns and stored in analog memories. If the event passes the first level trigger, the corresponding samples (typically five) are readout by the data acquisition system (see Section 1.2.6).

### Hadronic Calorimetry

Hadronic calorimetry at the LHC is mainly designed to identify jets and measure their energy and direction, and to measure the total missing transverse energy ( $E_T^{\text{miss}}$ ). Fragmentation, gluon radiation and the presence of magnetic fields are intrinsic effects that limit the resolution of these measurements. However, at LHC designed luminosity, the pile-up energy from minimum-bias events also becomes important. In order to be sensitive to interesting physics, an energy resolution of  $50\%/\sqrt{E} \oplus 3\%$  and segmentation of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  is required for the central region. For the forward region, a resolution of  $100\%/\sqrt{E} \oplus 10\%$  and segmentation of  $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$  is sufficient.

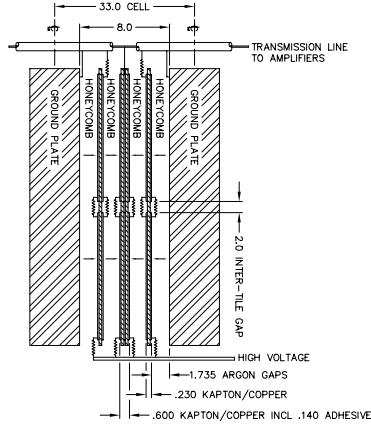
The ATLAS hadronic calorimetry covers a pseudo-rapidity range  $|\eta| < 5$ . Different techniques are used depending on  $\eta$ . The tile calorimeter covers  $|\eta| < 1.6$ . It is composed by a barrel and two extended barrels made out of plastic scintillating tiles as active medium. For  $1.5 < |\eta| < 4.9$  liquid-argon techniques are used for the two end-caps ( $1.5 < |\eta| < 3.2$ ) and the two high density forward calorimeters ( $3.2 < |\eta| < 4.9$ ). Both the hadronic end-caps and forward calorimeters are embedded into the same cryostat as the electromagnetic end-cap calorimeters.



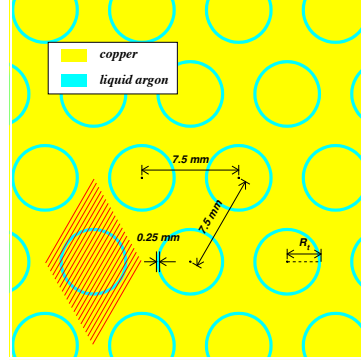
**Figure 1.6:** Drawing of the scintillating and iron tiles structure of the ATLAS hadronic tile calorimeter.

The ATLAS tile hadronic calorimeter (TileCal) [10] is a sampling calorimeter with steel plates as absorber and plastic scintillating tiles as active material (see Figure 1.6). The light produced in the scintillating tiles is collected through wavelength shifting fibers and readout by photomultipliers. The readout cells are defined by grouping together several fibers to the same photomultiplier, achieving three longitudinal samplings and a segmentation on  $\eta \times \phi$  of  $0.1 \times 0.1$  on the inner cells and  $0.2 \times 0.1$  on the outer cells. The analogue electrical signal of the photomultiplier is digitized in samples of 10 bits taken each 25 ns. These data are sent to the readout driver system where online reconstruction algorithms are applied. The tile calorimeter and the readout driver system is described in detail in Chapter 2.

The hadronic end-caps [9] are made up of two equal diameter wheels. The first wheel is built out of 25 mm copper plates as absorber and the second wheel uses 50 mm copper plates. Compared to iron, copper has a shorter interaction length and allows to increase the size of liquid-argon gaps between plates, thereby reducing the electronic noise, the integration time and pile-up noise. In both wheels the absorber plates are separated by 8.5 mm gaps filled with liquid-argon and a structure of three electrodes that divide the gap into four drift spaces of  $\sim 1.8$  mm (see Figure 1.7).



**Figure 1.7:** Sketch of the electrode structure of the hadronic end-cap calorimeters.

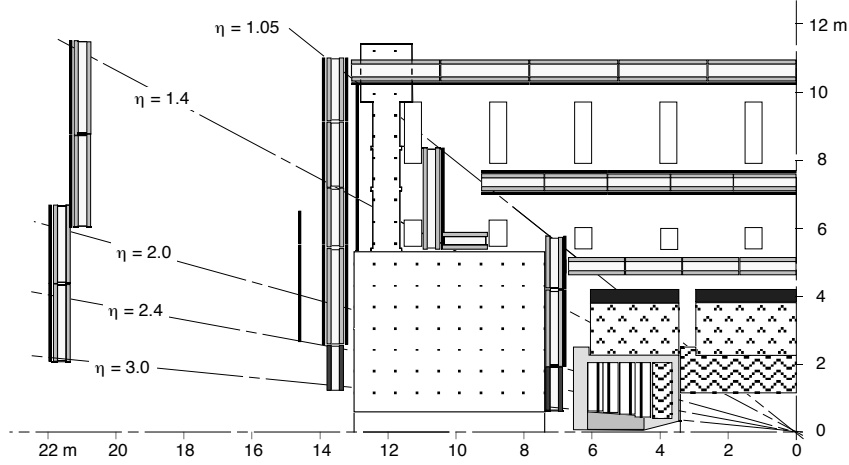


**Figure 1.8:** Sketch of the first section of the forward calorimeter readout.

The forward calorimetry [9] should be efficient on the forward jet tagging and  $E_T^{\text{miss}}$  reconstruction. The forward calorimeters are high density detectors in order to accommodate at least 9 interaction lengths of active material in rather short longitudinal space. Each forward calorimeter is divided into three longitudinal sections. In the first section the absorber is copper while in the second and third sections tungsten is used. The calorimeter consists of a metal matrix (the absorber) filled with rods (electrodes). The liquid-argon is the active medium and fills the gaps between the matrix and the rods (see Figure 1.8).

#### 1.2.4 Muon Spectrometer

A good momentum resolution is essential in order to detect the decay channels  $H \rightarrow ZZ^* \rightarrow 4\ell$  and  $Z' \rightarrow \mu\mu$ , as well as a good efficient trigger for low- $p_T$  muons in order to study B-physics. The ATLAS muon spectrometer [11] is designed to fulfill the following requirements: efficient use of the magnet bending power, pseudo-rapidity coverage of  $|\eta| < 3$ , projective towers on  $\eta$  and  $\phi$ , and finally practical chamber dimensions for production, transport and installation.



**Figure 1.9:** Side view of the ATLAS detector showing the position of the muon chambers.

Figure 1.9 shows the position of the muon chambers. The spectrometer is divided into three regions, barrel region ( $|\eta| < 1.05$ ), transition region ( $1.05 < |\eta| < 1.4$ ) and end-cap region ( $|\eta| > 1.4$ ). Four different technologies depending on the spatial and timing resolution, resistance to radiation and engineering considerations have been used: Monitored Drift Tube chambers (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC).

In the barrel region the chambers are situated in three concentric cylinders around the beam axis at 4.5 m, 7 m and 10 m. MDT chambers are used for high precision measurements and RPC for triggering. The low- $p_T$  muon trigger uses two double-layer RPCs located on each side of the middle station, while the high- $p_T$  trigger uses one triple layer chamber located at the outer barrel muon station.

In the transition and end-cap region most of the chambers are installed perpendicular to the beam axis (see Figure 1.9). In the intermediate region ( $1.05 < |\eta| < 1.4$ ) the muon track is measured with three vertical stations, placed inside or near the barrel magnet. In the end-cap region ( $|\eta| > 1.4$ ), the stations are lo-

cated before and after the end-cap toroid magnets and a third one near the cavern wall. The trigger is provided by TGC chambers while precision measurements are provided by MDT chambers at small  $\eta$  and CSC chamber at large rapidity.

The MDT chambers are composed by multilayers of high-pressure drift tubes. Each multilayer is mounted on each side of the support structure. The drift tubes are made of aluminum, 30 mm of diameter, with a central wire of W-Re. They work at 3 bar absolute pressure with a non-flammable mixture of Ar-CO<sub>2</sub>.

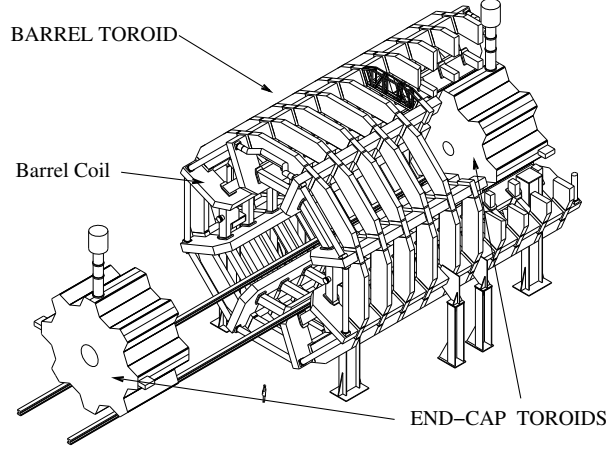
The CSCs are multiwire proportional chambers operated with a mixture of Ar-CO<sub>2</sub>-CF<sub>4</sub>. The distance between anode wires ( $\sim 2.5$  mm) equals the distance to the cathode. The cathode readout is segmented into strips (5.08 mm) orthogonal to the anode wires. The precision coordinate is obtained by measuring the induced avalanche in the segmented cathode, achieving space resolutions better than 60  $\mu\text{m}$ .

The RPC is a gaseous parallel-plate detector with a typical space-time resolution of  $1\text{ cm} \times 1\text{ ns}$  with digital readout. It is composed by two parallel resistive plates made of Bakelite. The plates are separated by spacers that define the size of the gas gaps. The gas is a mixture of C<sub>2</sub>H<sub>2</sub>F<sub>4</sub>. A uniform electric field of a few kV/mm produces the avalanche multiplication of ionization electrons. The signal is readout via capacitive coupling to metal strips placed at both sides of the detector and grounded.

A TGC is built with 50  $\mu\text{m}$  wires separated 2 mm. The wires are placed between two graphite cathodes at a distance of 1.6 mm. Behind the graphite cathodes, strips or pads are located to perform a capacitive readout in any desired geometry. Some advantages of these chambers are a fast signal, typical rise time 10 ns and low sensitivity to mechanical deformations.

### 1.2.5 Magnet System

The magnet system consists of a solenoid and air-core toroids. The solenoid provides inside the inner detector a magnetic field of 2 T. In order to minimize



**Figure 1.10:** Sketch of the superconducting air-core toroid magnet system.

the dead material in front of the calorimeter, the solenoid is placed inside the vacuum vessel of the EM LAr calorimeter barrel cryostat. The solenoid has a radius of 1.22 m and length of 5.3 m and covers the whole inner detector.

The second magnet system is composed by three air-core superconducting toroids, one for the barrel and two for the end-caps. They are designed to produce a large volume field, covering  $|\eta| > 3$  for the muon spectrometer. The barrel length is 26 m and the inner and outer diameter are 9.4 m and 19.5 m, respectively. The end-cap toroids are located at each side of the barrel. Their inner bore is 1.26 m and their length 5.6 m. Each toroid (barrel and end-caps) consist of 8 coils situated radially around the beam axis (see Figure 1.10). The barrel toroids are placed inside individual cryostats with common cold wall. The cryostat interconnections form a structure of rings along the toroid. This structure allows an easy insertion of the muon chambers. The 8 coils of each end-cap toroid are inserted in a common cryostat.

### 1.2.6 Trigger and Data Acquisition

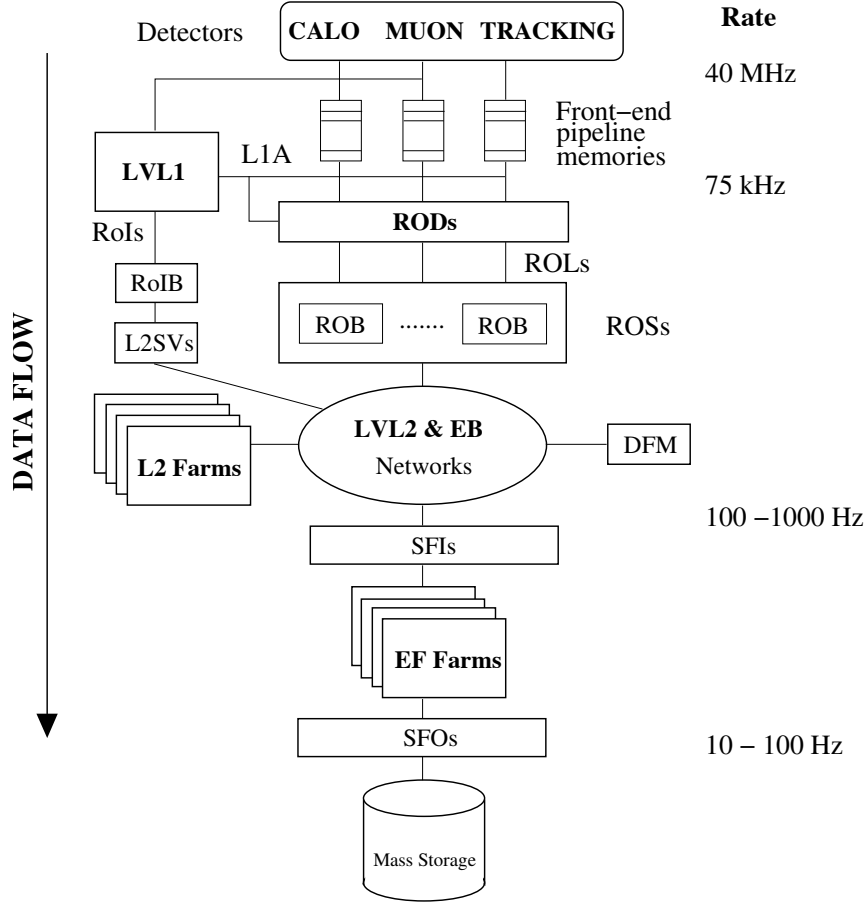
Assuming a luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , the LHC will produce an average of 19 proton-proton interactions at a frequency rate of 40 MHz. The ATLAS trigger system should reduce this rate down to  $\sim 100 \text{ Hz}$ . At the end of the chain, the size of each event should be around 1.5 MB, therefore a storage capability of  $\sim 100 \text{ MB/s}$  is also required.

The ATLAS trigger [12] is divided in three levels (see Figure 1.11). The First level trigger (LVL1) has dedicated processors acting on data with reduced granularity from calorimeters and the muon spectrometer. The Second level trigger (LVL2) uses the full granularity from most detectors, but acts only on a reduced region selected by the LVL1. The third level is the event filter (EF), acting on the full event and taking the final decision before data storage. LVL2 and EF are part of the high level trigger system (HLT).

The LVL1 accepts data input at the LHC bunch-crossing rate of 40 MHz from calorimeters and the muon spectrometer. The maximum time allowed to take a decision is  $2 \mu\text{s}$ . Meanwhile data is stored in pipeline memories in the so-called front-end electronics. The LVL1 reduces the output rate to 75 kHz and identifies unambiguously the bunch-crossing that contains the interaction of interest.

Events accepted by the LVL1 trigger are sent to the readout drivers (RODs) of all the detectors. The RODs should be able to process on real time these events. In particular, the RODs of the tile hadronic calorimeter reconstruct the energy deposited in the calorimeter cells as well as the arrival time of the signal and a quality factor of the reconstruction. The implementation and performance of this algorithm is further explained in Chapter 3. The ROD system sends the data to the readout system (ROS) composed by several readout buffers (ROBs).

The LVL2 acts on the requested fragments from selected ROBs. The LVL2 reduces the event rate from 75 kHz to  $\sim 1 \text{ kHz}$ . It uses information from LVL1 trigger in order to identify regions of interest (RoIs). These regions contain poten-



**Figure 1.11:** Diagram of the principal components of the DataFlow and High Level Trigger systems.

tially interesting signals such as high  $p_T$  EM clusters, jets or muons. The latency time is variable and may reach 10 ms.

After LVL2 selection, data is sent to the event filter farm. The decision time is about 1 s. The EF farms process the whole event with complete information from all detectors. This last selection should provide a final storage rate of 10 - 100 MB/s, either reducing the rate or the size of the event.



## 1.3 ATLAS Software

### 1.3.1 Full Simulation

The complexity of the physics events to be analyzed at the LHC and the diversity of the detectors to be integrated into ATLAS imply an absolute necessity to provide an accurate detector simulation, in order to evaluate the detector and physics performance in detail. The ATLAS simulation program has been developed continuously since 1990, using initially the GEANT-3 package [13], written in FORTRAN, and since 2000 the GEANT-4 package [14] written in C++. All simulated data up to the so-called DC1 (Data Challenge 1) were produced using the GEANT-3 package, then the switch over to the GEANT-4 package took place. The ATLAS simulation program can be logically divided into three separate modules: event generation, detector simulation and digitization. These three parts communicate through a set of data structures (ZEBRA banks for the FORTRAN version, and object oriented (OO) structures for the C++ version).

In addition to describing the detector geometry and tracking particles through it, the GEANT framework is used to describe the materials constituting the detector, to visualize the detector components, and to simulate and record the response of the sensitive elements of the various systems. When simulating a very complex detector such as ATLAS, the simulation software has to take into account as many physics processes as possible, covering the broadest possible range of energies. Ideally, the program should be able to simulate physics processes with energies as low as 10 eV (*e.g.* ionization potential in the active gas of various detectors) and as high as a few TeV (*e.g.* catastrophic energy losses of muons traversing the calorimeters). The most challenging task in terms of consumption of CPU time is an accurate simulation of showers in the calorimeters.

The description of the ATLAS geometry in GEANT is probably the most critical issue for the detector simulation program, since it must represent the right compromise between accuracy and performance. All the ATLAS subdetectors have been described to a very high level of detail. Inactive material (cryostats, support structures, services, *etc.*) has been given a great emphasis, and an accurate de-

scription of both its layout and material distribution has been introduced wherever possible. These inactive parts of the detector have often been shown to have a direct impact on the physics performance of the experiment and therefore have to be evaluated very carefully. The numbers of GEANT volumes used to describe the geometry of the various ATLAS systems are shown in Table 1.2, where they can be compared to the total number of active detector elements or equivalently to the number of independent readout channels and to the total number of modules or chambers. In many systems each active cell is described explicitly, using sometimes up to ten volumes or more per cell. In contrast, details like the pixel or microstrip structure of the silicon detectors, or the cell structure of the barrel accordion calorimeter, have not been described in the geometry itself, but only introduced afterward at the digitization level in order to increase the flexibility and the performance of the simulation chain.

**Table 1.2:** Number of active detector elements, number of modules or chambers, and number of GEANT volumes defined for the detailed simulation of each of the various ATLAS detector systems.

| <b>Detector system</b>                           | <b>Active<br/>elements</b> | <b>Modules<br/>or chambers</b> | <b>GEANT<br/>volumes</b> |
|--------------------------------------------------|----------------------------|--------------------------------|--------------------------|
| Pixels                                           | 140 000 000                | 2 200                          | 26 000                   |
| Silicon microstrips                              | 6 280 000                  | 4 100                          | 50 000                   |
| Transition radiation<br>tracker                  | 420 000                    | 240                            | 2 260 000                |
| LAr accordion<br>calorimeters                    | 170 000                    | 48                             | 9 960 000                |
| LAr hadronic end-cap and<br>forward calorimeters | 9 000                      | 134                            | 890 000                  |
| Tile Calorimeters                                | 10 000                     | 192                            | 900 000                  |
| Muon System                                      | 1 230 000                  | 2 000                          | 1 850 000                |

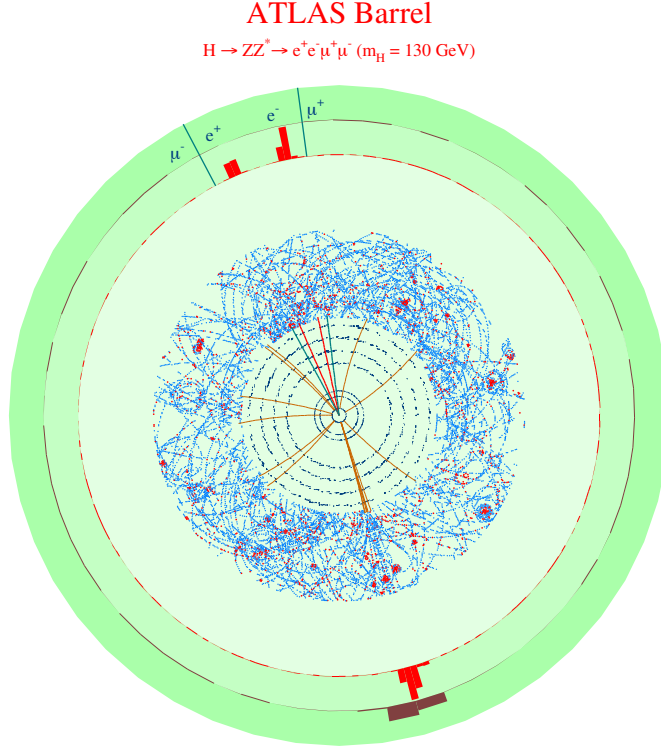
The event generation phase is normally run separately in order to have a consistent input stream which can be used many times. The most widely used event generators (PYTHIA, HERWIG and ISAJET) are interfaced to GEANT. Ad hoc

single-particle generators and test-beam geometries have also been developed for detector-specific studies. Particle filter algorithms can be applied, in order not to track particles outside the geometrical acceptance of the detector or with an energy below a certain threshold, thus achieving a significant gain in CPU time.

The digitization step is a second level of detector simulation, placed just at the interface with the reconstruction program, where the physical information is registered and reprocessed in order to simulate the detector output, and eventually written out to be used by the reconstruction programs. The output from the digitization is obtained in a form similar to the expected one from the readout electronics in the actual experiment. This step was in fact originally conceived to give the user the possibility of changing the readout characteristics (for instance, the strip pitch in the silicon detectors or the cell granularity in the EM calorimeter) immediately after the detector simulation step, thus gaining considerably in the amount of CPU time needed during the phase of detector optimization. Detailed signal treatment (for instance, the most accurate possible treatment of  $dE/dx$  in the TRT or digital filtering in the calorimeters), simulation of the front-end electronics behavior, noise injection, *etc.*, can also be performed at this level. The digitization step is very fast, except when pile-up at high luminosity is included. It is often therefore rerun as the first step in the reconstruction chain, if noise levels or single-channel efficiencies in some of the detectors are to be varied.

### 1.3.2 Reconstruction

The reconstruction of particles and other physics objects in the ATLAS detector has been developed over many years, and was initially implemented in a program called ATRECON, mostly written in Fortran77 and using ZEBRA as memory manager. At present a new framework called ATHENA [15] is in use, written in C++ and with a fully object-oriented design. ATRECON runs on simulated GEANT-3 data and ATHENA includes the GEANT-4 simulation package. The reconstruction proceeds in two stages. First, data from each detector is reconstructed in a stand-alone mode. Second, the information from all detectors is combined to get the most accurate measurements and identification of the final objects used in the analysis: photons, electrons, muons, leptons, Kaons, jets, b-jets,  $E_T^{\text{miss}}$ , primary



**Figure 1.12:** Display in the transverse plane of a simulated high- $p_T$   $H \rightarrow ZZ^* \rightarrow ee\mu\mu$  decay at a luminosity  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ .

vertex, *etc.* . . . The output of the various algorithms is stored in standardized combined n-tuples, which allows analysis in a PAW [16] framework, or in ESD/AOD structures to be analyzed using ROOT [17]. Figure 1.12 shows a view of a high- $p_T$  reconstructed  $H \rightarrow ZZ^* \rightarrow ee\mu\mu$  decay, with reconstructed tracks in the inner detector and the muon system and with the reconstructed energy clusters of the two electrons and a high- $p_T$  jet in the calorimeters.

Hit coordinates are reconstructed in the precision tracker and in the TRT. Tracks from charged particles are searched for. Two rather different algorithms with comparable performances have been developed:

- iPatRec starts from a combinatorial search in the precision tracker, and

- xKalman finds tracks in the TRT with a histogramming method and follows them inward using Kalman-filtering techniques.

Track reconstruction can be performed over the full inner detector, or over limited range around *seeds* found by the other detectors (electromagnetic clusters, jets, muons) and around Monte Carlo truth information for checks. The use of seeds in the reconstruction algorithm can save a factor of up to 100 in CPU time for events including the pile-up expected at high luminosity. It is possible to run LVL1 and LVL2 trigger algorithms prior to reconstruction.

In a second stage, information from several detectors is combined. Muons reconstructed in the muon system are refined by matching the track to an inner detector track. This improves the momentum resolution, especially at moderate  $p_T$ , and yields accurate track parameters at the vertex. Lower- $p_T$  (down to 2 GeV) muons are found by matching an inner detector track to the tile calorimeter cells. Photon conversions and  $K_s$  decays are searched for by pairing inner detector tracks. The primary vertex is reconstructed using all the tracks in the event. High- $p_T$  (above 10 GeV) photon identification requires electromagnetic cluster shower-shape variables and the absence of reconstructed tracks in the inner detector, except for identified conversions. High- $p_T$  electron identification requires a track reconstructed in the inner detector with transition-radiation hits and a measured momentum matching a calorimeter energy deposition compatible with an electromagnetic shower. Softer non-isolated electrons (down to  $p_T$  of 1 GeV) are identified by extrapolating inner detector tracks to the EM calorimeter. Finally,  $\tau$ -leptons are identified from narrow jets associated with a small number of charged tracks. Candidate b-jets are tagged by algorithms combining the impact parameter of high-quality tracks or by vertexing algorithms.

### 1.3.3 Fast Simulation and Reconstruction

Fast particle-level simulation and reconstruction is an intermediate step between simple parton-level analysis of the event topology, which in general yields much too optimistic results for physics processes at hadron colliders, and very sophisticated and CPU-consuming full detector simulation and reconstruction. This kind of

approach is needed for quick and approximate estimates of signal and background rates for specific channels. In addition, fast simulation and reconstruction is the only practical tool for high-statistics studies of complex background processes. A complete package for fast detector simulation and physics analysis has been implemented over the past few years and exists in two versions:

- ATLFAST, the FORTRAN implementation of the algorithm [18], interfaced to PAW, and
- ATLFAST++, the OO/C++ implementation of the same algorithm [19], interfaced to ROOT.

ATLFAST can be used for fast simulation of signal and background processes, including the most crucial detector aspects: jet reconstruction in the calorimeters, momentum/energy smearing for leptons and photons, magnetic field effects and missing transverse energy. It provides, starting from the list of particles in the event, a list of reconstructed jets, isolated leptons and photons, the expected missing transverse energy, and reconstructed charged tracks. Values for the rejections against non-b-jets are also provided as a function of the efficiencies for identifying b-jets. In most cases, the detector-dependent parameters are tuned to what is expected for the performance of the ATLAS detector from full simulation and reconstruction.

The ATLFAST package aims to reproduce as well as possible the expected detector performance in terms of resolution and particle-identification for important physics signals. It does not attempt, at present, to reproduce accurately the expected efficiencies for lepton and photon isolation. In the case of hadronic jets, the jet reconstruction (and veto) efficiency is often dominated by physics effects, which are straightforward to model in the fast simulation. For any specific channel, the predictions from ATLFAST in terms of resolution and reconstruction efficiency, should always be confirmed with full-simulation results. The acceptances, jet reconstruction efficiencies, jet-veto efficiencies, and mass resolutions have shown good agreement between fast and full simulations. Not all the detector effects can be readily parametrized in fast simulation and only the basic information of the detector geometry is used in the package. This basic information is for ex-

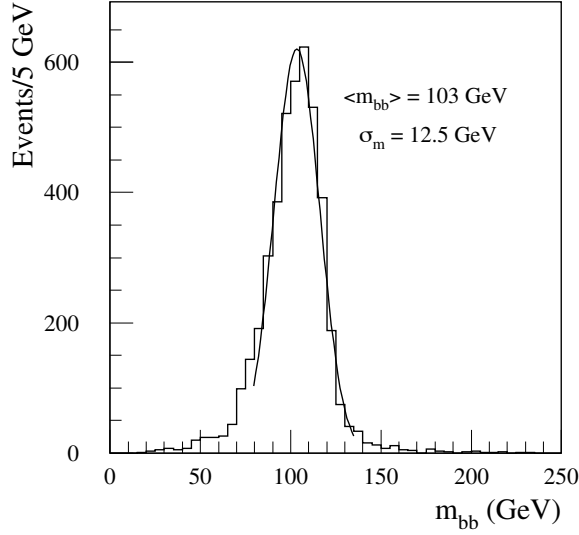
ample: the coverage for precision physics and for the calorimetry, the size of the barrel/end-cap transition region for the EM calorimeter, and the granularity of the hadronic calorimeters. No effects related to the detailed shapes of particle showers in the calorimeters, the charged track multiplicity in jets, *etc.*, are taken into account. In particular, energy isolation of leptons is only simulated in a crude way.

To illustrate the consistency between fast and full simulation and reconstruction, the mass reconstruction of the WH with  $H \rightarrow b\bar{b}$  process with  $m_H = 100$  GeV is presented in Figure 1.13 using ATLFAS. Jets with  $p_T > 15$  GeV before energy recalibration are accepted and the efficiency for reconstruction is about 80% per b-jet from fast and full simulation. The mass peak can be reconstructed with an expected resolution of 15 GeV with full simulation (and 12.5 GeV with fast simulation) and a correct position of the peak in the distribution (after jet energy recalibration), nevertheless with some fraction of the signal appearing as non-Gaussian tails. Most of these effects can be attributed to the final-state radiation and hadronization.

### 1.3.4 Event generators

There are several available Monte Carlo event generators for pp collisions, such as HERWIG [20], ISAJET [21] and PYTHIA [22]. Each of these simulates a hadronic final state corresponding to some particular model of the underlying physics. The details of the implementation of the physics are different in each of these generators, however the underlying philosophy of the generators is the same.

The basic process is a parton interaction involving a quark or gluon from each of the incoming protons. Elementary particles in the final state, such as quarks, gluons or W/Z bosons, emerge from the interaction. The fundamental process is calculated in perturbative QCD, and the initial momentum of the quarks or gluons is given by structure functions.



**Figure 1.13:** Distribution of reconstructed invariant mass,  $m_{b\bar{b}}$  as obtained using fast simulation of WH production with  $m_H = 100$  GeV and  $H \rightarrow b\bar{b}$  decay at low luminosity operation.

Additional QCD (gluon) radiation takes place from the quarks and gluons that participate in the basic scattering process. These parton showers are based on the expansions around the soft and collinear limits and can be ascribed to either the initial or final state. The algorithm used by HERWIG includes some effects due to quantum interference and generally produces better agreement with the data when detailed jet properties are studied. The showering continues down to some low energy cut-off. For some particular cases the matrix element calculations involving higher-order QCD processes are used. The events that have more energy in the parton process have more showering, and consequently more jet activity.

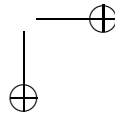
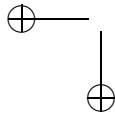
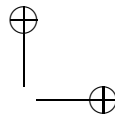
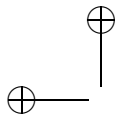
The collection of quarks and gluons must then be hadronized into mesons and baryons. This is done differently in each of the event generators, but is described by a set of fragmentation parameters that must be adjusted to agree with experimental results. HERWIG looks for colour singlet collections of quarks and gluons with low invariant mass and groups them together. This set then turns into hadrons. PYTHIA splits gluons into quark-antiquark pairs and turns the re-



sulting set of colour singlet quark-antiquark pairs into hadrons via a string model. ISAJET simply fragments each quark independently paying no attention to the colour flow.

Matrix elements are likely to provide a better description of the main character of the events, *i.e.* the topology of well separated jets, while parton showers should be better at describing the internal structure of these jets. The above model describes events where there is a hard-scattering of the incoming partons: either a heavy particle is produced or the outgoing partons have large transverse momentum. While these are the processes that are of most interest, the dominant cross-section at the LHC consists of events with no hard scattering. There is little detailed theoretical understanding of these minimum-bias events and the event generators must rely on data at current energies. These minimum-bias events are important at LHC, particularly at high luminosity, as they overlap interesting hard-scattering events such as the production of new particles. The generators use a different approach in this case. ISAJET uses a pomeron model that has some theoretical basis. HERWIG uses a parametrization of data mainly from the CERN pp collider. PYTHIA uses a mini-jet model where the jet cross-section is used at very low transverse momenta, *i.e.* the hard scattering process is extrapolated until it saturates the total cross-section. Whenever relevant, ATLAS has used the PYTHIA approach with dedicated modifications that agree with present data from the Tevatron. The multiplicity in minimum-bias events predicted by this approach is larger than that predicted by ISAJET or HERWIG.

Despite the huge efforts which have been put into developing physics generators for hadron colliders over the last years, the precision with which present data can be reproduced is not better than 10 – 30%, and in some cases is not better than a factor of two. In the work presented here, cross-sections are normally computed using leading-order QCD implemented in PYTHIA 6.2, using the CTEQ5L [23,24] set of structure functions as a reference. Whenever better or more appropriate calculations are available, the production cross-section from PYTHIA is suitably normalized, or a different Monte Carlo generator is used.



## Chapter 2

# The TileCal Read-Out Drivers

*“Every great and deep difficulty bears in itself its own solution. It forces us to change our thinking in order to find it.”*

— Niels Bohr, 1885 – 1962

### 2.1 The Tile Hadronic Calorimeter

#### 2.1.1 Basic principles

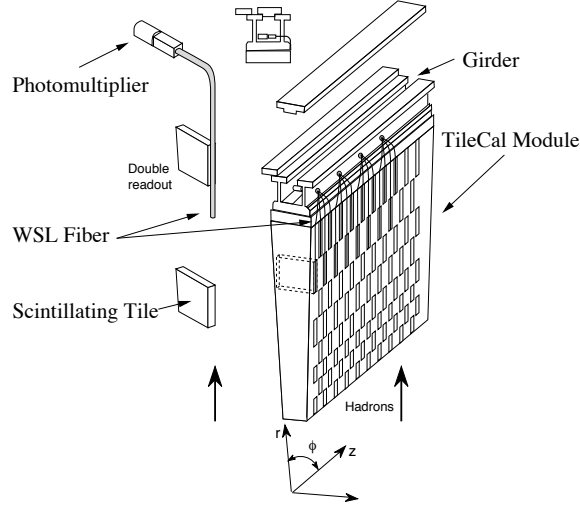
The ATLAS Tile Calorimeter (TileCal) is a sampling calorimeter made out of iron as absorber material and plastic scintillating tiles as active medium [10]. The absorber structure is built from separated laminate structures with pockets at periodic intervals that contain the scintillating tiles. This structure is connected to a massive girder which provides the magnetic flux return of the ATLAS solenoid and shields the read-out electronics and photomultiplier tubes housed inside. The

light produced in the scintillating tiles is collected by wavelength shifting (WLS) fibers along the two sides of a module. The scintillating tiles and the WLS fibers are adequately fast; therefore, the read-out electronics can collect the whole signal and not only a fraction. Moreover, the use of fibers allows to define three dimensional read-out cells and create a projective geometry for the trigger and energy reconstruction. The so-called, front-end electronics are placed in the outer radius of the detector, inside the girder of each module. Several fibers are routed to the same photomultiplier (PMT), defining in this way the read-out cells. The two sides of a module are read-out by different PMTs, this feature provides redundancy on the signal that may be needed during the ATLAS operating period of around 10 years.

The scintillating tiles are oriented in the same direction as the incoming particles (see Figure 2.1). Therefore, local variations of the sampling fraction are expected and, consequently, variations in the calorimeter response. These variations depend on the lateral dimensions of the shower and on the distance between active elements. A thinner shower, like electron showering, and large separation between tiles implies larger effects on the sampling variations. However, this effect decreases at larger incident angles. In TileCal, this effect is observed during test beam analysis [10], nevertheless it should decrease if there is around 2 interaction length of absorber material in front of the calorimeter, as it is the case for ATLAS. The largest part of the shower is deposited before TileCal, and the part entering in TileCal is mainly produced by particles traveling in different direction from the initial ones, which deeply decreases the effect. Moreover, due to the orientation of the active material, signal non-uniformities at the boundaries between different calorimeter modules did not occur [25].

### 2.1.2 Mechanics

TileCal is mechanically composed by a long central barrel and two extended barrels. The inner and the outer radius of the cylinders are 2280 mm and 4230 mm, respectively. The central barrel is 5640 mm long in the direction of the beam axis, while each extended barrel is 2919 mm long. Each cylinder is divided into 64 independent modules along the azimuthal direction. There is a gap of 600 mm



**Figure 2.1:** Diagram showing the Tile Calorimeter design.

between the central and the extended barrels. This gap is needed for the cables and services of the inner and the liquid argon detectors.

The central barrel covers the pseudorapidity region of  $-1 < \eta < 1$  and the extended barrels  $0.8 < |\eta| < 1.7$ . A stepped calorimeter structure is placed in part of the gap between the barrels, the intermediate tile calorimeter (ITC). The ITC tries to maximize the active material in this region while leaving enough space for cables and services. The ITC consists of a plug calorimeter between  $0.8 < |\eta| < 1$ , and scintillators between  $1 < |\eta| < 1.6$ . The scintillators are divided into Gap scintillators, between  $1 < |\eta| < 1.2$  and Crack scintillators, between  $1.2 < |\eta| < 1.6$ .

PMTs and front-end electronics are installed in movable drawers inside the girder structure in order to allow fast access. Two drawers of 1.5 m long are sequentially inserted from the two sides of the central barrel and from one side of the extended barrels, segmenting the calorimeter in 4 read-out barrels (2 central and 2 extended). A total of 512 identical drawers are needed for the whole calorimeter.

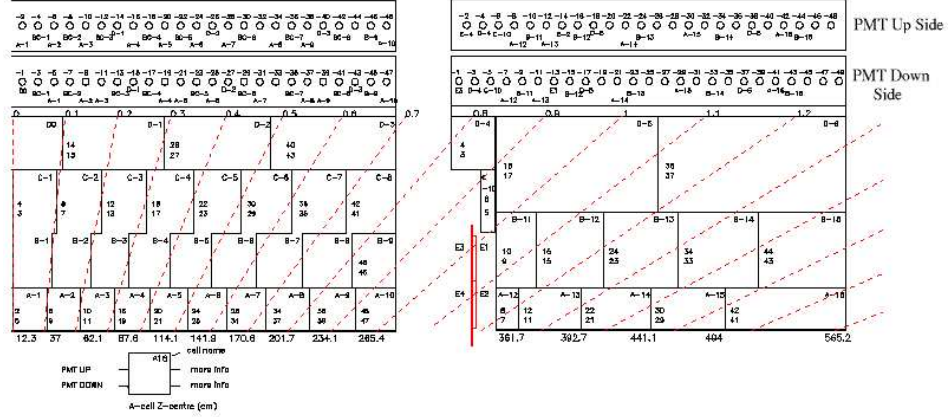
### 2.1.3 Optics

Ionizing particles crossing the tiles induce the production of light in the base material of the tiles, with wavelength in the UV range which subsequently is converted to visible light by scintillator dyes. This scintillation light propagates through the tile to its edges, where it is absorbed by the WLS fibers and shifted to a longer wavelength (chosen to match the sensitive region of the PMT photocathode). A fraction of the light re-emitted in the fibers is captured and propagated via total internal reflection to the PMTs where it is detected. A light mixer is placed between the fibers and the photocathode to optimize detection uniformity.

Scintillating tiles are produced by injection molding. The base material is an optically transparent granulate polystyrene doped with two scintillating additives, PTP and POPOP. Tiles are wrapped with a special material, Tyvek<sup>TM</sup>, in order to protect the surface and improve the uniformity. There are 11 different types of tiles with trapezoidal shape, though the thickness is always 3 mm. The azimuthal length may vary between 200 and 400 mm and the radial length varies between 97 and 187 mm. Each tile has two holes of 9 mm of diameter for the insertion of the tubes for calibration sources. Around 460 000 tiles are needed to fill the whole calorimeter.

Around 1120 km of WLS fibers have been used for transmitting the scintillation light from the tiles to the PMTs. The fibers have a diameter of 1 mm and are air-coupled radially to the two sides of each tile. The WLS fibers incorporate a fast shifter (with decay time of 10 ns) that absorbs the blue light from the tiles and re-emits it with a larger wavelength. The end of the fiber, opposite to the PMT, is aluminized in order to obtain a reflectivity of  $\sim 85\%$ .

The structure of the calorimeter read-out cells is obtained by grouping the signal of several fibers to the same photomultiplier. Figure 2.2 shows the projective distribution of the cells for the central and the extended barrels. Redundancy on the signal is obtained because the same cell is read-out by two different PMTs that collect the fibers from each side of the tiles. Each module is longitudinally segmented in three samplings, A, BC and D. This segmentation allows to study



**Figure 2.2:** Drawing of the TileCal cell distribution for half a central barrel module (on the left) and an extended barrel module (on the right). Dashed lines show the pseudorapidity projective distribution.

the longitudinal distribution of the showers for particle identification. A direct application of this is the so-called MuTag algorithm, that identifies low transverse momentum muons in the tile calorimeter [26, 27]. The proposed segmentation of the calorimeter with the doubled read-out requires 9 856 read-out channels including the two extended and the central barrels.

### 2.1.4 Electronics

Detailed simulations of TileCal show maximum energy depositions of 2 TeV. At the LHC full luminosity, these depositions are expected of the order of a few per year. In addition, the calorimeter should also be able to measure low signals from muons of about 0.5 GeV in the smallest cell. If the signal from muons is required to be around 15 counts the dynamic range needed for the calorimeter is 60 000 counts or 16 bits. For hadrons that interact only in the tile calorimeter the resolution obtained from beam tests is [3]

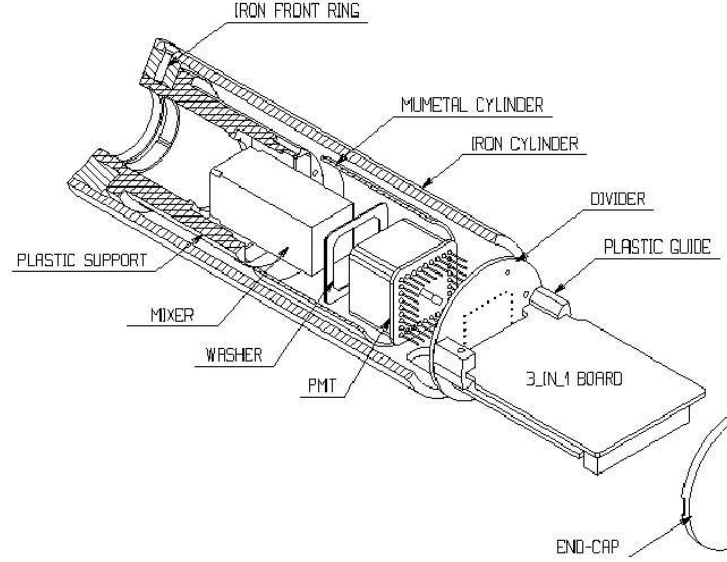
$$\frac{\sigma}{E} = \frac{47\%}{\sqrt{E}} + 2\% . \quad (2.1)$$

The overall design of the TileCal front-end electronics is simple and compact; all front-end and digitizing electronics are situated in the back-beam region of the calorimeters, on the so-called drawers. The drawers are movable and can be inserted into the girder. Always two drawers are combined to a 3 m long unit, called super-drawer. The super-drawer of half central barrel module contains 45 PMTs and the super-drawer of an extended barrel module 32 PMTs. The high voltages (HV) of the PMTs are regulated by special boards in the drawer. Pipelines and digitizers are locally installed. The digital information is transferred to the RODs in the counting room via a few optical fibers.

The read-out is divided in two subsystems, the PMT blocks and the super-drawers. The function of a PMT block is to convert the light from the scintillating tiles into current signals. Each PMT block is composed of four parts: a light mixer, a photomultiplier tube, a HV divider and a 3-in-1 card (see Figure 2.3). The PMT blocks are located in holes inside the rigid aluminium structure of the drawers and are inserted in a  $\mu$ -metal cylinder to provide magnetic shielding of up to 200 G in any direction. A light mixer is placed between the fiber bundle and the photocathode to mix the light coming from the fibers, so that, there is no correlation between the position of a fiber and the area of the photocathode which receives the light. Several studies have been made in order to select the best photomultiplier. It was found that Hamamatsu R5900 was the best choice. They are very compact ( $28 \times 28 \times 28 \text{ mm}^3$ ) and their dinode structure incorporates between 8 and 10 amplification stages. The rise time is around 1.4 ns, which provides a fast response to the excitation. The needed voltage is around 800 V being the limit of ATLAS requirements of 1000 V and the sensitivity to magnetic fields is very low, as well as the non-linearity, which less than 1 %.

The voltage divider is implemented in the 3-in-1 board, using a printed circuit with surface mounted device (SMD) components. The high voltage is organized in two stages. First, a high voltage power supply provides to each drawer a single voltage of 1 kV at a current 10 mA, and second, controllers in each drawer distribute the individual voltages to the PMTs using optocontrollers that allow to adjust the voltage in a range of 400 V. Most of the analogical functions are implemented in the 3-in-1 card [28]. One function is the shaping of the PMT pulse,

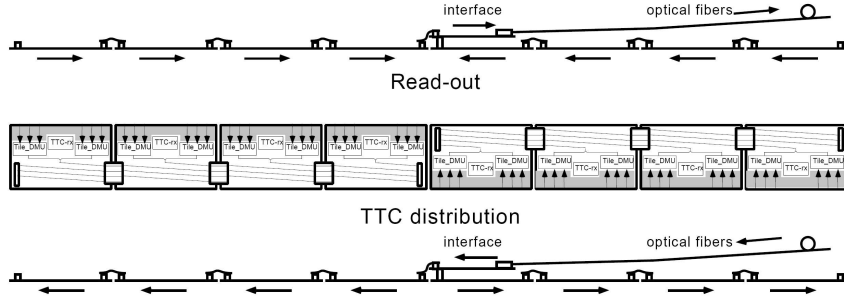




**Figure 2.3:** Drawing of the PMT block showing the main components.

producing two output linear pulses (low and high gain pulses) with relative gain of 64, allowing a 16 bit dynamic range using only 10-bit ADCs. The 3-in-1 cards also produce a fast analog signal for the Trigger Summation Card at the 1st level trigger. Moreover, they incorporate a charge integration system for calibration and monitoring and a charge injection system for injecting a known charge over the full dynamic range for calibration also.

The electronic boards are connected to motherboards which are situated on the top and the bottom sides of the drawer. A super-drawer from a central barrel holds 8 digitizer boards (6 for an extended barrel) each serving 6 read-out channels (see Figure 2.4). Digitizer boards are divided into analog and digital part. The analog part contains twelve 10-bit ADCs in order to sample the signal from 6 channels with two gains. The digital part stores the samples around  $2 \mu\text{s}$  until the 1st level trigger takes a decision. If the event is selected, samples from the corresponding bunch crossing and from previous and subsequent bunch crossings are stored in derandomizer memories. The number of samples stored is programmable, being



**Figure 2.4:** Diagram of the digitizer data flow in a super-drawer. The grey part of the digitizer boards is analog.

the maximum number of samples 16. All this is done in a custom designed ASIC, the TileDMU. Each digitizer board is equipped with two TileDMUs.

Data from all digitizers is sent directly to an interface card placed in the middle of the super-drawer [29]. Its main functionality is to receive the TTC optical signal and distribute it to the 8 digitizer boards of a central barrel module (or to the 6 digitizer boards of an extended barrel module) and to the control motherboard. Additionally, the interface card receives the data from the digitizer boards, aligns and sorts it into event frames before being sent via an optical G-link to the off-detector read-out driver crate at a data rate of 640 Mbit/s.

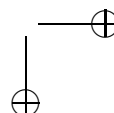
Each TileDMU receives 10 bits of high gain and 10 bits of low gain from three different read-out channels [30]. Then, four parity bits are added before storing the data into the pipeline memory. The size of this memory is programmable and can be adjusted depending on the first level trigger latency. When a L1A signal arrives,  $n$  consecutive samples are queue in a derandomizer buffer before being read-out. The number of samples,  $n$ , is also programmable, the central sample corresponds to the L1A bunch crossing. The samples are compared to a low and high level limits in order to select one of the two gains. A 32-bit header word, that will be read-out first, is build up. After the header,  $n$  32-bit data words are added (if running in normal mode) for the selected gain or  $2n$  data words (if running in calibration or test mode) with both gains included (high and low). A serializer

## 37

**Figure 2.5:** Description of a 32-bit header word. The least significant bits are on the right.

The 32-bit header word contains information about the number of samples, the gain of the three read-out channels managed by the corresponding TileDMU, the read-out mode (normal, calibration or test) and the bunch crossing identifier. Additional bits for transmission error checks are also included as well as an odd parity bit. The most significant bit (MSB) is set to 1 to easily identify the header word. Figure 2.5 shows a detailed description of a header word.

The interface card receives through an LVDS-bus the 2-bit stream of each TileDMU, a clock and several control lines. Data is then collected and stored in an event frame and sent via G-link transmitter (the HPMP-1032 from Agilent Technologies) to the ROD crate at 640 Mbit/s. Inside the interface card, the 2-bit wide input data is re-aligned to 32-bit words. The 32-bit stream is sent to 16-bit word G-link



| 31 | 29 | 20                                | 19 | 10                                | 9 | 0                             |
|----|----|-----------------------------------|----|-----------------------------------|---|-------------------------------|
| 0  | P  | Sample 1 from channel $(j + 2)$   |    | Sample 1 from channel $(j + 1)$   |   | Sample 1 from channel $(j)$   |
| 0  | P  | Sample 2 from channel $(j + 2)$   |    | Sample 2 from channel $(j + 1)$   |   | Sample 2 from channel $(j)$   |
| 0  | P  | ...                               |    | ...                               |   | ...                           |
| 0  | P  | ...                               |    | ...                               |   | ...                           |
| 0  | P  | Sample $n$ from channel $(j + 2)$ |    | Sample $n$ from channel $(j + 1)$ |   | Sample $n$ from channel $(j)$ |

0: Data word bit  
P: Parity (odd) bit

**Figure 2.6:** Description of the data block in normal mode. The index  $j$  corresponds to the read-out channel number and runs from 0 to 47 and  $n$  is the total number of digitized samples. The least significant bits are on the right. If calibration or test mode is selected both gains are included, first low and then high gain.

serializer. First, a start of event word set to 0x511151110 and sent before the 16 blocks from the 16 TileDMU chips. Then, a serial CRC error word is added. The bits of this word are set to 1 if there are no previous errors on the CRC-16 check sum of even and odd bits, otherwise are set to 0 (0xFFFFFFFF for the central barrel module and 0x0FFF0FFF for an extended barrel module if there are no errors). A global CRC16-CCITT word is sent with the 16 MSB set to 0 and the 16 LSB set to the calculated value. The last word sent is the end of event set to 0xFFFFFFFF0. Figure 2.7 shows a detailed description of the back-end input data format running in normal mode.

The input data format that arrives to the RODs is the same for a central barrel module (45 read-out channels) and for an extended barrel module (32 read-out channels). The data stream always contains 16 blocks with 3 channels each, which makes a total of 48 channels. Figures 2.8 and 2.9 show the mapping of the read-out channels to the corresponding PMT cells, for both central and extended barrel modules respectively. If the PMT number is negative means that this channel is not used.

| Nb.<br>words | Normal mode<br>data      |           | Description        |
|--------------|--------------------------|-----------|--------------------|
| 1            | 0x51115111               |           | Start control word |
| 2            | Header word              |           | TileDMU 1          |
| 3            | Data word 1              |           |                    |
| 4            | Data word 2              |           |                    |
| 5            | Data word 3              |           |                    |
| ...          | ...                      |           |                    |
| $n + 2$      | Data word $n$            |           |                    |
| $n + 3$      | CRC-16 even ∷ CRC-16 odd |           |                    |
| $n + 4$      | Header word              |           | TileDMU 2          |
| $n + 5$      | Data word 1              |           |                    |
| $n + 6$      | Data word 2              |           |                    |
| $n + 7$      | Data word 3              |           |                    |
| ...          | ...                      |           |                    |
| $2n + 4$     | Data word $n$            |           |                    |
| $2n + 5$     | CRC-16 even ∷ CRC-16 odd |           |                    |
| ...          | ...                      |           | TileDMU ...        |
| ...          | ...                      |           | TileDMU ...        |
| $15n + 32$   | Header word              |           | TileDMU 16         |
| $15n + 33$   | Data word 1              |           |                    |
| $15n + 34$   | Data word 2              |           |                    |
| $15n + 35$   | Data word 3              |           |                    |
| ...          | ...                      |           |                    |
| $16n + 32$   | Data word $n$            |           |                    |
| $16n + 33$   | CRC-16 even ∷ CRC-16 odd |           |                    |
| $16n + 34$   | Even check               | Odd check | TileDMU chip mask  |
| $16n + 35$   | 0x0000                   | CRC16     | Global CRC16-CCITT |
| $16n + 36$   | 0xFFFFFFFF0              |           | End control word   |

**Figure 2.7:** Description of the back-end input data format for normal mode, where  $n$  is the number of samples. If calibration or test mode is selected, both gains are sent (first low and then high gain) within each TileDMU data block.

| Central barrel module |         |     |  |         |         |     |
|-----------------------|---------|-----|--|---------|---------|-----|
| TileDMU               | Channel | PMT |  | TileDMU | Channel | PMT |
| 1                     | 0       | 1   |  | 9       | 24      | 27  |
|                       | 1       | 2   |  |         | 25      | 26  |
|                       | 2       | 3   |  |         | 26      | 25  |
| 2                     | 3       | 4   |  | 10      | 27      | 30  |
|                       | 4       | 5   |  |         | 28      | 29  |
|                       | 5       | 6   |  |         | 29      | 28  |
| 3                     | 6       | 7   |  | 11      | 30      | -33 |
|                       | 7       | 8   |  |         | 31      | -32 |
|                       | 8       | 9   |  |         | 32      | 31  |
| 4                     | 9       | 10  |  | 12      | 33      | 36  |
|                       | 10      | 11  |  |         | 34      | 35  |
|                       | 11      | 12  |  |         | 35      | 34  |
| 5                     | 12      | 13  |  | 13      | 36      | 39  |
|                       | 13      | 14  |  |         | 37      | 38  |
|                       | 14      | 15  |  |         | 38      | 37  |
| 6                     | 15      | 16  |  | 14      | 39      | 42  |
|                       | 16      | 17  |  |         | 40      | 41  |
|                       | 17      | 18  |  |         | 41      | 40  |
| 7                     | 18      | 19  |  | 15      | 42      | 45  |
|                       | 19      | 20  |  |         | 43      | -44 |
|                       | 20      | 21  |  |         | 44      | 43  |
| 8                     | 21      | 22  |  | 16      | 45      | 48  |
|                       | 22      | 23  |  |         | 46      | 47  |
|                       | 23      | 24  |  |         | 47      | 46  |

**Figure 2.8:** TileDMU mapping for a central barrel module, correspondence between read-out channels and PMTs, negative numbers identify channels that are not used.

| Extended barrel module |         |     |  |         |         |     |
|------------------------|---------|-----|--|---------|---------|-----|
| TileDMU                | Channel | PMT |  | TileDMU | Channel | PMT |
| 1                      | 0       | 1   |  | 9       | 24      | -27 |
|                        | 1       | 2   |  |         | 25      | -26 |
|                        | 2       | 3   |  |         | 26      | -25 |
| 2                      | 3       | 4   |  | 10      | 27      | -31 |
|                        | 4       | 5   |  |         | 28      | -32 |
|                        | 5       | 6   |  |         | 29      | -28 |
| 3                      | 6       | 7   |  | 11      | 30      | 33  |
|                        | 7       | 8   |  |         | 31      | 29  |
|                        | 8       | 9   |  |         | 32      | 30  |
| 4                      | 9       | 10  |  | 12      | 33      | -36 |
|                        | 10      | 11  |  |         | 34      | -35 |
|                        | 11      | 12  |  |         | 35      | 34  |
| 5                      | 12      | 13  |  | 13      | 36      | 44  |
|                        | 13      | 14  |  |         | 37      | 38  |
|                        | 14      | 15  |  |         | 38      | 37  |
| 6                      | 15      | 16  |  | 14      | 39      | 43  |
|                        | 16      | 17  |  |         | 40      | 42  |
|                        | 17      | 18  |  |         | 41      | 41  |
| 7                      | 18      | -19 |  | 15      | 42      | -45 |
|                        | 19      | -20 |  |         | 43      | -39 |
|                        | 20      | 21  |  |         | 44      | -40 |
| 8                      | 21      | 22  |  | 16      | 45      | -48 |
|                        | 22      | 23  |  |         | 46      | -47 |
|                        | 23      | 24  |  |         | 47      | -46 |

**Figure 2.9:** TileDMU mapping for an extended barrel module, correspondence between read-out channels and PMTs, negative numbers identify channels that are not used.

## 2.2 The Read-Out Driver System

### 2.2.1 Introduction

The ROD system is part of the TileCal back-end electronics. One of its main functionalities is to feed the 2nd level trigger with information of the energy deposited in the calorimeter cells and other relevant quantities, such as timing of the signal and quality factor of the reconstruction. When a L1A signal arrives, the ROD system receives digitized data from the TileCal front-end electronics through high-speed optical links. The processing of this data inside the RODs should be done in less than 10  $\mu$ s, which is the 1st level trigger rate. Therefore, the ROD system provides real-time processing without introducing dead time in the ATLAS acquisition chain.

Additionally, the ROD system provides VME communication for controlling and monitoring of the electronic boards. It also synchronizes the incoming data with the trigger information and generates a busy signal in order to stop the L1A signal generation if needed. Moreover, a mechanism for error detection and handling is implemented in order to check the consistency of the data. Furthermore, the ROD system provides access to internal histograms produced in the ROD processing units during an acquisition run without introducing dead time.

### 2.2.2 System setup

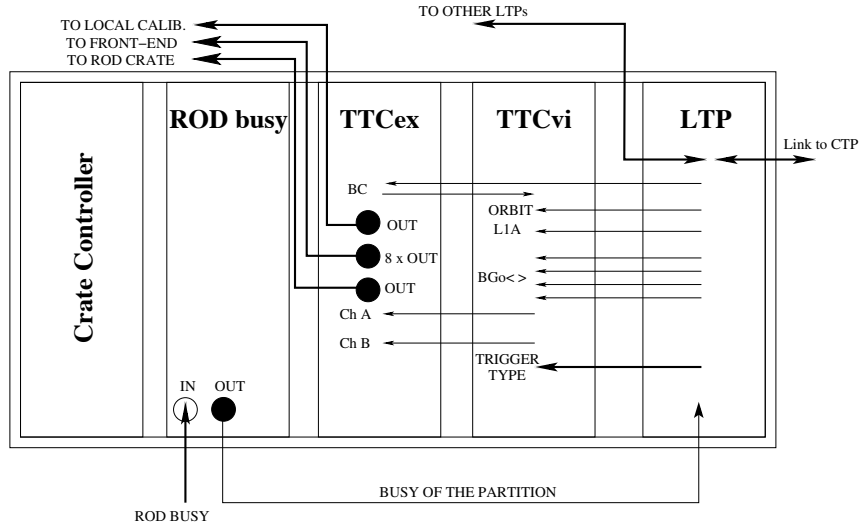
The read-out of the whole tile calorimeter is segmented in 4 independent partitions. In the final configuration, each partition reads-out one barrel of the calorimeter (two central and two extended barrels). Each partition has an associated TTC crate to deal with TTC information and a ROD crate to read-out and process the data. There are two possible modes of running, global or local. During global mode, TTC signals are received from the central trigger processor (CTP) and data is acquired using the global ATLAS central data acquisition (DAQ) system during an ATLAS global run. During local mode, the calorimeter is able to run in stand-alone mode, and TTC signals are generated by local electronics [31].



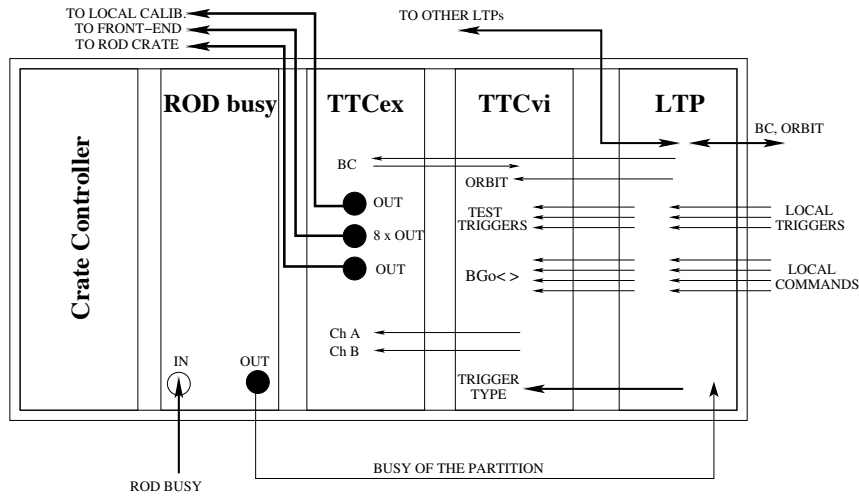
A TileCal TTC crate is basically composed by a VME crate controller, which is a 6U VME module with a CPU, and 4 additional modules: a local trigger processor module (LTP), a TTCvi module, a TTCex module and a ROD busy module (see Figure 2.10 and 2.11). The crate controller accesses and controls all the boards through the VME bus, it is always placed in slot number one of the TTC crate. The LTP module is the interface between the TTCvi and the trigger source, that can be either the CTP or local electronics. The connection of the LTP module with the CTP is done through a differential link. The LTP link can be daisy chained to other LTP modules of the same subdetector. This minimizes the number of links from the CTP to the subdetectors and allows to connect easily several partitions when running in local mode. The TTCvi module provides the TTC information through the signals of A- and B-channels to the TTCex which multiplexes and encodes these signals before sending them to the front-end electronics, to a TTCpr card, during local calibration runs, and to the ROD crate via optical link. Finally, the ROD busy module receives the busy signal from the ROD crate and provides a global busy signal to the trigger source.

During global mode, the CTP receives the bunch clock (BC) and the orbit signal from the LHC machine, even though the machine is down. The CTP provides to each partition with the BC, orbit, L1A, Trigger-type, Event counter reset (ECR) and pre-Pulse signals and receives an 'OR' of the busy signals and 3-bits for calibration requests from each partition. There is a mechanism to acquire calibration during physics runs via calibration requests. Figure 2.10 shows the connections inside the TTC crate during global mode runs. During local mode, BC and orbit signal are still available in the ATLAS pit, otherwise they can be generated internally by the LTP or the TTCvi. The additional signals are generated by local electronics. Figure 2.11 shows the connections inside the TTC crate during local mode run. For the tile calorimeter 4 custom 6U VME board, the SHAFT boards, accept the LHC TTC and CTP signals (BC, orbit, *etc.*) and generate calibration triggers and calibration requests that are sent to the LTPs of the 4 TTC partitions.

The ROD crate receives from the TTCex the TTC information through an optical fiber and sends back the ROD crate busy signal to the ROD busy module. The ROD crate is a standard ATLAS 9U VME crate. Each crate holds a VME



**Figure 2.10:** Connections of the TTC modules inside the TTC crate when running in global mode.



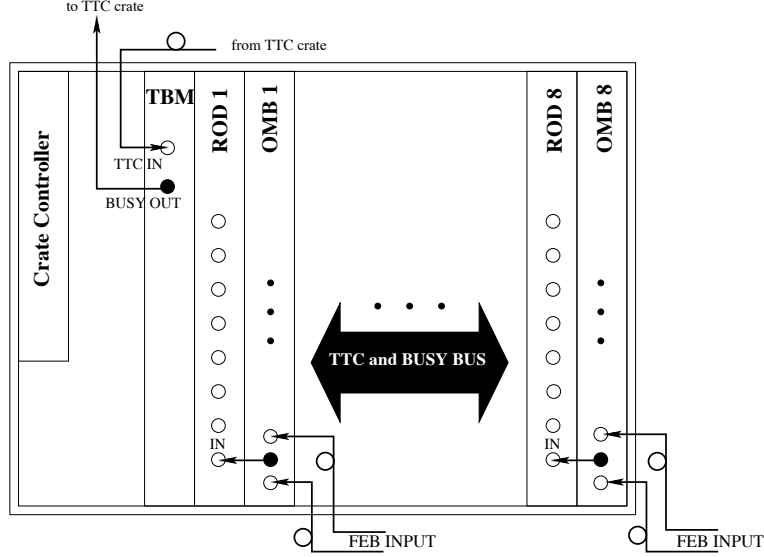
**Figure 2.11:** Connections of the TTC modules inside the TTC crate when running in local mode.

crate controller, a trigger and busy module (TBM), up to 8 optical multiplexer boards (OMB) and up to 8 ROD motherboards with a transition module (TM) associated. The distribution of these modules inside the ROD crate is shown in Figure 2.12.

The crate controller is a 6U VME module with a CPU for the initialization of the modules as well as monitoring and support of the VME access (for configuration and data transfer). The VP-110 from Concurrent Technologies is the standard accepted by the ATLAS collaboration. The TBM is a 9U VME module which receives the trigger signals from the TTC crate. The TBM distributes the TTC information over a custom P3 backplane. Through this backplane the TBM also receives the busy signals from the ROD motherboards and produces a logical 'OR' to generate a ROD crate busy signal which is sent to the TTC crate. The front-end electronics sends identical data via two fibers from each super-drawer for redundancy, the OMB receives both fibers, implements a CRC check to monitor transmission errors and sends one of the fibers to the corresponding ROD motherboard. The ROD motherboard is a 9U VME module that can read-out up to 8 optical fibers of data, which means information from 8 different super-drawers. It can hold up to 4 mezzanine cards, called processing units (PU), used to process the data online before sending it to the transition module installed at the back of the VME crate. The TMs are placed just behind each ROD module, they receive the data through the P2 and custom P3 backplane and transmit it to the ROS via optical fibers. For this reason, the TMs are equipped with 2 s-link [32] mezzanine cards that convert the electrical signal into optical.

### 2.2.3 The ROD motherboard

The TileCal ROD motherboard [33] is based on the liquid argon ROD motherboard design. Figure 2.13 shows a sketch of the TileCal ROD motherboard with the associated transition module. Each ROD motherboard has 8 optical receivers (ORX). These ORXs are mezzanine boards that receive the optical signals from 8 super-drawers (after the fiber selection in the OMB). Then, 8 G-link chips (HDMP-1024) deserialize the incoming data and send it to 4 staging FP-GAs (Field Programmable Gate Arrays) together with additional protocol signals

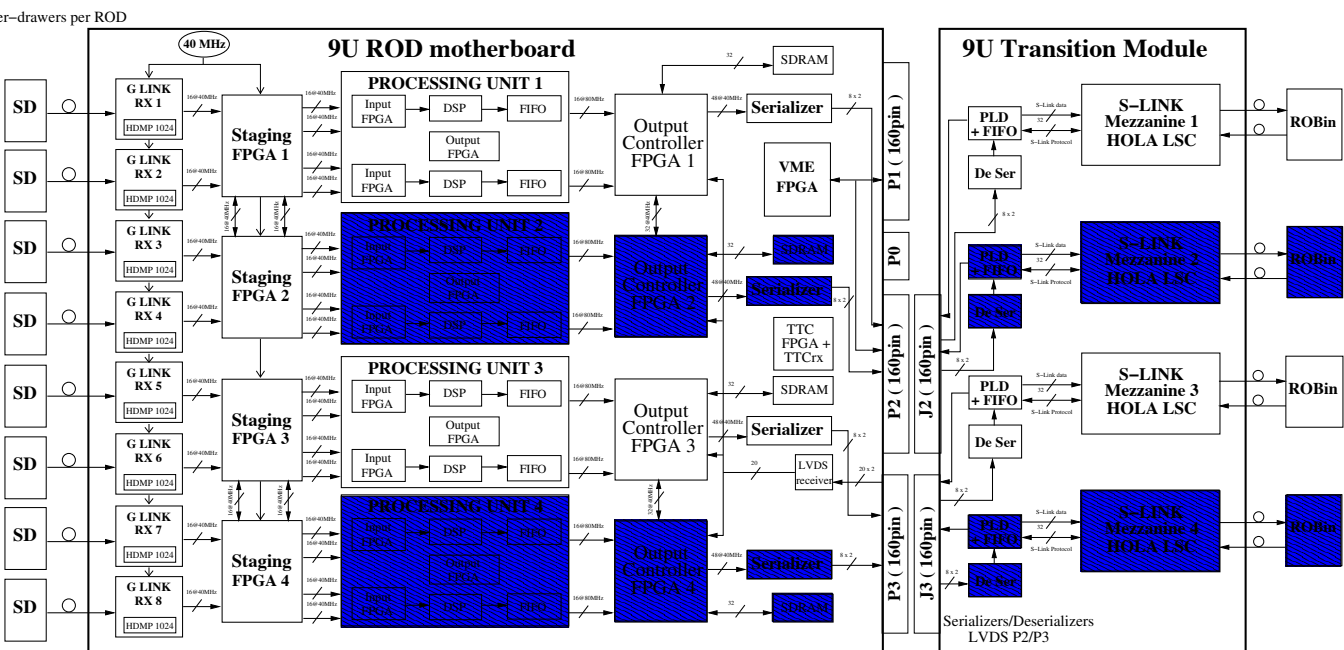


**Figure 2.12:** Distribuion and connection of the ROD modules inside the ROD crate.

(control, clock locked, error signal, *etc.*). The staging FPGAs (ACEX EP1k50) route the input data to the processing units. There are two operation modes:

- **normal mode** where data from two fibers is gathered to one processing unit and
- **staging mode** where data from four fibers is gathered to one processing unit.

The selected LHC configuration is staging mode, in this case, only two processing units per ROD are needed. The staging FPGAs also monitor the G-link temperature. In the design of the ROD motherboard, from the liquid argon collaboration, a PLL (Phase-Locked-Loop), is placed near the staging FPGA to double the TTC clock frequency (from 40.08 MHz to 80.16 MHz). In the TileCal ROD motherboard this clock was changed to a clock with the same frequency as the TTC clock (40.08 MHz). With this new clock and using air-cooling, the temperature of the G-links keeps stable well within chip specifications [34].



**Figure 2.13:** Schematic diagram of the ROD motherboard and the transition module associated. Components in dark are not needed in staging mode, which is the LHC final configuration.

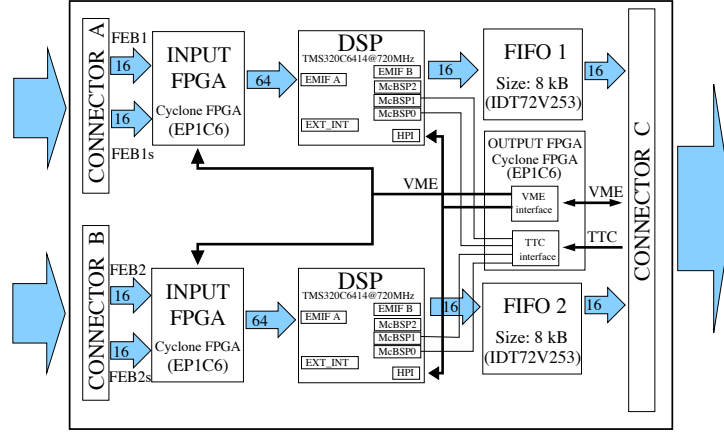
An ACEX EP1k100 is used as output controller FPGA (OC). There are four OC in a ROD motherboard. The OCs read the data from the FIFOs of the processing units and send it either to an SDRAM, to be read through VME, or to a serializer chip, to send the data to the TM through the P2 and custom P3 backplane.

The VME interface is implemented in an FPGA ACEX EP1k100. The ROD module is considered a VME slave and can be accessed by the ROD crate controller. The data bus is D32 (32-bit data words) and the addressing is A32 (32-bit address words) for data transfer. A description of the software to access and control the ROD modules can be found in [35].

The trigger information is received at the ROD level from the TBM through the P3 backplane. This information is decoded by the TTCrx chip and managed by the TTC FPGA (APEX EP1k100) which sends the TTC information to the corresponding PU. The TTC FPGA also distributes the clock signal to all the components of the motherboard.

Online data processing is done by the PUs which are mezzanine cards connected to the ROD motherboards via 3 connectors. This configuration was chosen because allows future upgrades of the ROD processing power without introducing much additional cost. Each ROD can hold up to 4 PUs although running in staging mode only 2 PUs are needed. Each PU is equipped with two input FPGAs, two digital signal processors (DSPs), two output FIFOs and an output FPGA. Figure 2.14 shows a diagram of a ROD processing unit.

The PU output FPGA implements the interface between the PU components and the ROD motherboard, it provides the TTC information and the access to the VME bus. The input FPGAs receive the data from the staging FPGAs. Data is then checked and can be pre-processed before being sent to the DSPs. When the event is ready, an interruption is sent to the DSP, then the DSP launches a direct memory access (DMA) to read the data through the 64-bit external memory interface bus A (EMIFA). The DSP processes the data in real time at the level 1 trigger frequency of 100 kHz. The main functionality of the DSPs is to reconstruct the



**Figure 2.14:** Schematic diagram of a ROD processing units.

energy deposited in the calorimeter cells. This energy is proportional to the amplitude of the read-out signal. The optimal filtering algorithm (OF) reconstructs the amplitude and the phase of the signal by means of a weighted sum of the digitized samples. The weights are upload to the DSPs using a host port interface (HPI) at initialization time or before starting a run. The implementation of the OF algorithm inside the DSPs and the performance results are shown in Chapter 3. After data processing and formatting, the result is sent to the output FIFO through a 16-bit bus. TTC information is received by the output FPGA and sent to the DSP through two serial ports (McBSP0 and McBSP1). The McBSP0 receives the BCID and the event identifier (EvID) while the McBSP1 receives the trigger type. In order to boot the DSPs, the DSP code is encoded and sent through VME to the DSP HPI at initialization time. Histograms and internal registers of the DSP are also accessible through the same port. Via the third serial port McBSP2, the DSP can receive configuration commands and parameters such as run number, processing routine type, configuration mode, *etc.* . Moreover, the output FPGA sends also configuration commands and the TTC information to the input FPGA and allows to boot this FPGA through VME without shutdown of the system.

## 2.3 The Digital Signal Processor in the ROD

### 2.3.1 Why a digital signal processor?

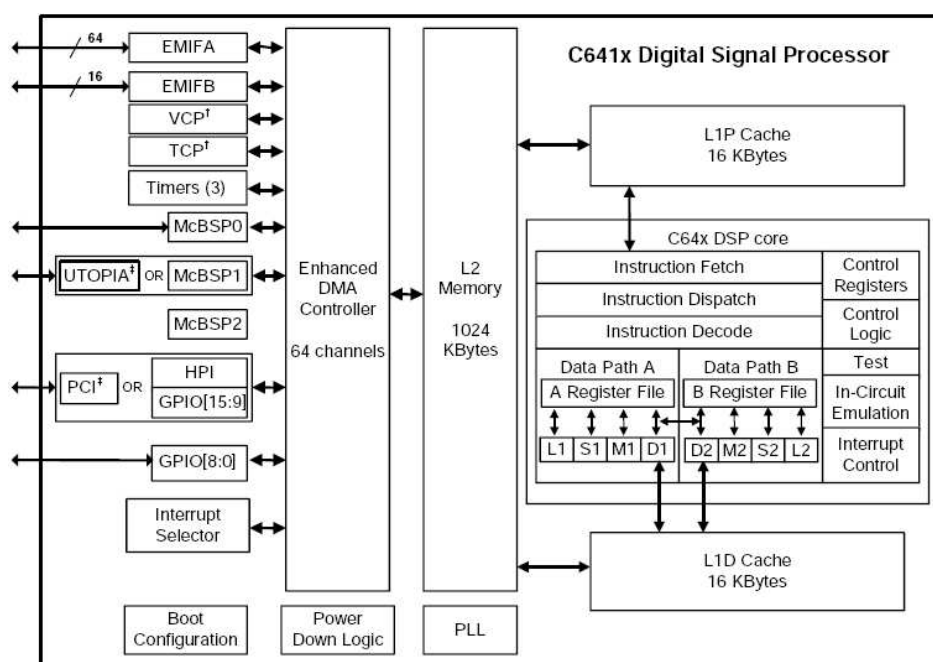
The ROD processing units are equipped with the TMS320C6414<sup>TM</sup> DSPs of Texas Instruments in order to execute reconstruction algorithms in real time. The choice of DSPs over similar devices, *e.g.* FPGAs, is justified. The DSPs can apply different algorithms depending on the trigger type of the data: physics, pedestal, laser, charge injection, *etc.* and can be programmed in high level languages, such as C language, which are simpler to maintain and to adapt to the detector requirements. This is needed because the selected device should be flexible for future upgrades of the reconstruction algorithms depending on the LHC conditions which may vary along its life. Moreover, the commercial DSPs implement easily MAC (multiply-accumulative) instructions which are the base of standard data filtering algorithms. They have also an internal local memory where input and output data is stored using a circular buffer. Another useful feature of the DSPs is the access through a host port interface and serial ports which allows to re-configure the DSPs at running time, read histograms from these devices and load new calibration constants for the reconstruction algorithms.

### 2.3.2 The TMS320C6414 DSP

The TMS320C6414 DSP from Texas Instruments [36] belongs to the TMS320C6000<sup>TM</sup> family of fixed-point DSPs. The TMS320 DSPs have an architecture specifically designed for real time processing. They use a high performance advanced VelociTI<sup>TM</sup> very long instruction words (VLIW) architecture (VelociTI.2<sup>TM</sup>). This architecture consists on multiple execution units that can run in parallel which allows to perform multiple instruction in a single clock cycle.

Figure 2.15 shows the block diagram for the TMS320C64x. This DSP has separated program and data memories that can be used as program and data cache, respectively. It is also provided with peripherals such as a DMA controller, power-down logic, external memory interface (EMIF), serial and parallel host ports.





**Figure 2.15:** Diagram of the TMS320C641x DSP. The VCP/TCP only exists for the C6416 device and UTOPIA and PCI for the C6415 devices.

The DSP CPU is composed by a program fetch unit, instruction dispatch unit and instruction decode unit that can deliver up to eight 32-bit instructions to the functional units every CPU clock cycle. There are two data paths (A and B), each one provided with four functional units, three ALUs and one multiplier, and 64 32-bit general purpose registers.

The internal memory of the chip is organized in a level-one cache (L1) of 32 kB, separated in 16 kB of program memory space (L1P) and 16 kB of data memory space (L1D), and a unified program and data memory space of 1024 kB that can be used as SRAM or level-two cache (L2). The L1P is direct-mapped, it has a 256-bit wide data path to the DSP core, so that the DSP core may fetch up to 8 32-bit instructions every single clock cycle. The L1D is two-way associative, it allows two simultaneous data accesses from the two DSP core data paths, so the DSP core can load or store two 64-bit values in a single data cycle.

A DMA and EDMA controllers transfer data between address ranges in the memory map without intervention by the CPU, and a host processor can directly access the memory space through a parallel port (HPI). The EMIF bus acts as host port and as I/O port that can operate in synchronous mode or asynchronous. The McBSPs are serial ports. These ports can buffer serial samples in memory automatically with the aid of the DMA controller. These DSPs are also provided with timers and power-down logic. Table 2.1 shows a summary of the main features of the TMS320C6414 DSP.

## 2.4 The TileCal detector testbeam and commissioning

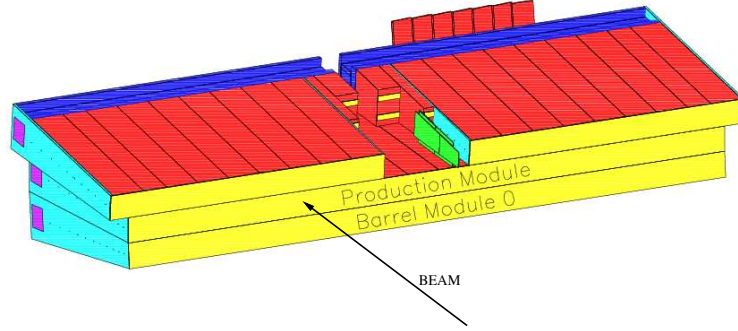
The response of the ATLAS tile hadronic calorimeter is being studied during several years in order to guarantee a good performance during the LHC runs. First, the response of 11 % of the TileCal production modules were tested with beam particles, composed typically by electrons, muons and hadrons, in a range of

**Table 2.1:** Main features of the TMS320C6414 DSP.

| Features             | TMS320C6414               |
|----------------------|---------------------------|
| Cycle time           | 1.39 ns                   |
| Clock rate           | 720 MHz                   |
| Instruction/cycle    | 8 32-bit instructions     |
| Functional units     | (6) ALUs, (2) multipliers |
| Data memory (L1D)    | 16 kB                     |
| Program memory (L1P) | 16 kB                     |
| Level-two cache (L2) | 1024 kB                   |
| EDMA                 | 64 channels               |
| EMIF                 | (1) 16-bit, (1) 64-bit    |
| Host port            | (1) 32-/16-bit HPI        |
| McBSP                | 3                         |
| Timers               | (3) 32-bit                |
| Core supply          | 1.4 V                     |
| IO supply            | 3.3 V                     |

energies between 3 and 350 GeV [10]. Then, after the assembly of the calorimeter in the underground experimental hall UX15 (the ATLAS cavern), TileCal is being commissioned using the final electronics and software with cosmic muons.

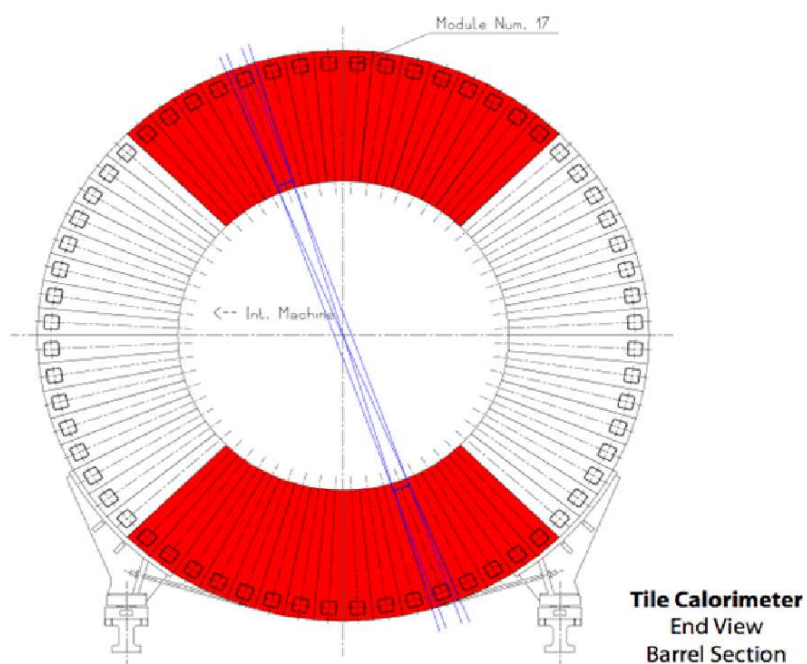
Using beams of electrons, the energy-to-charge conversion factors are calculated for the 11 % of the production modules, these values are extrapolated to the rest of the modules, using cesium calibration to achieve a similar response for all the modules. The uniformity of the cells within a module is also studied using muons, which behave as minimum ionizing particles when traversing the calorimeter. The results obtained with muons and electrons are then extended to hadrons. Additionally, monitor and calibration systems are checked. Moreover, these tests provide a good opportunity to study different methods of digital signal reconstruction algorithms.



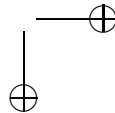
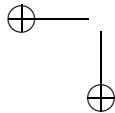
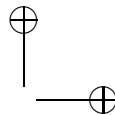
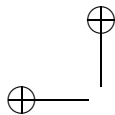
**Figure 2.16:** Drawing of the configuration of the TileCal modules during test beam period.

During the test beam period a beam of hadrons, muons and electrons was used. The identification of the particles was done using the calorimeter segmentation and two Cerenkov counters. The trigger was provided by the coincidence of three beam scintillator counters (in addition to calibration triggers, for pedestal, charge-injection, laser, *etc.*). Particles impinged a module in the selected  $\eta$  direction, as shown in Figure 2.16. A reference module (Barrel Module 0) and two central barrel modules (or one central and two extended) are installed in a movable table. With this configuration the beam can impact the modules with different angles.

During commissioning, a program of cosmic rays data acquisition is planned for TileCal. The trigger is provided by the TileCal trigger electronics, using custom coincidence boards which take as input up to 192 TileCal trigger tower analog signal [37]; half in the top part and half in the bottom part. A signal coincidence in the upper and lower part of the calorimeter triggers the data acquisition (see Figure 2.17). The energy deposited by these muons is very small and consequently the read-out signal, however, this setup is extremely adequate to test the full acquisition chain and the online reconstruction algorithms implemented in the RODs.



**Figure 2.17:** Drawing of the configuration of the TileCal modules and cosmic muon trigger during commissioning period.



## Chapter 3

# Digital Signal Reconstruction

*“The more physics you have the less engineering you need.”*

— Ernest Rutherford, 1871 – 1937

### 3.1 Introduction

The digitized samples generated by the ATLAS hadronic tile calorimeter contain the information about the energy deposited by a particle when it travels through the calorimeter. In order to extract this information from the samples three different algorithms have been studied, the Flat Filtering algorithm, the Fit method and the Optimal Filtering algorithm. The three algorithms provide the deposited energy, Flat Filtering is based on the estimation of the signal area and Fit method and Optimal Filtering are based on the estimation of the signal amplitude.

The best energy resolution is achieved with Fit method and Optimal Filtering, however, mathematically speaking the application of Optimal Filtering is much simpler than the application of Fit method. Thus Optimal Filtering is the algorithm proposed to reconstruct the energy on real time running on tile calorimeter Read-Out Driver boards, where the processing time is one of the big constraints [38, 39]. This chapter describes the Optimal Filtering algorithm and the procedure to calculate the OF weights.

The Optimal Filtering algorithm is designed to account for the LHC conditions where the digitization clock is synchronized with the trigger clock, thus the signal samples have always a fixed phase upon small variations. However, during testbeam and commissioning the digitization clock is not synchronized with the trigger clock, and the digitized samples have phases in a wide range. An iterative method is also proposed in this chapter that accounts for the phase shift. A comparison between Fit and Optimal Filtering using this iterative procedure is shown for pions at 180 GeV taken during testbeam period, a good agreement is obtained between the two algorithms.

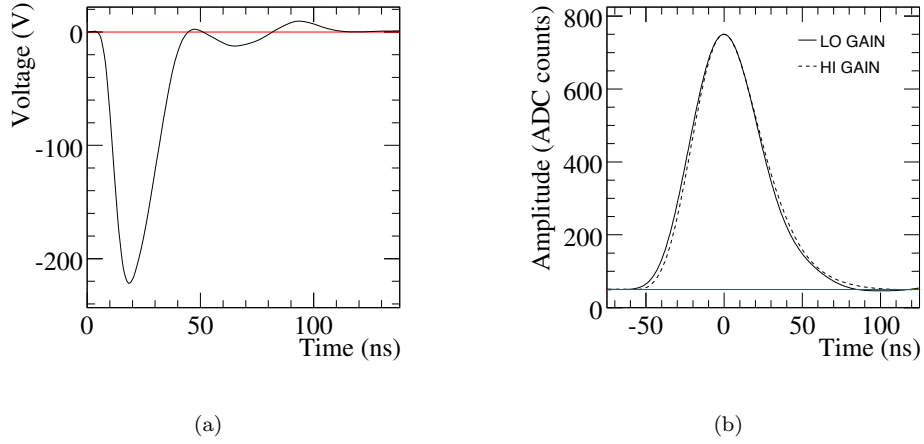
The Optimal Filtering is currently implemented in the digital signal processors of the TileCal RODs, and is tested with cosmic muons data. This chapter describes the online implementation of the Optimal Filtering algorithm in the RODs and the proposed output data format to send the reconstruction parameters to the ATLAS 2nd level trigger. To conclude, a comparison of the online reconstruction using Optimal Filtering and the offline reconstruction using Fit is also done, showing agreement on the energy reconstruction around 99 % for energies larger than  $3\sigma_{\text{noise}}$ .

## 3.2 Digital signal reconstruction algorithms

### 3.2.1 The Optimal Filtering algorithm

A particle traveling through the tile calorimeter deposits part of its energy in the scintillating tiles. This energy is then converted into light which is driven to

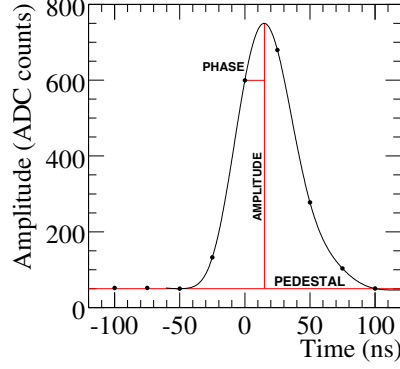




**Figure 3.1:** (a) Voltage generated by a TileCal PMT as function of time under the light of a pulsed led. (b) Reconstruction of the digitized pulse after the whole read-out chain, for low gain (solid line) and high gain (dashed line).

PMTs via WLS optical fibers. The PMTs convert the light into a fast signal of electrical current, then this signal is shaped and amplified in order to match the TileCal electronics requirements. Afterward we obtain two pulses (high and low gain with gain ratio of 64) of around 150 ns wide. Figure 3.1(a) shows the pulse generated by a TileCal PMT while Figure 3.1(b) shows the reconstructed pulse after the whole read-out chain. The main feature of the final pulse is that its amplitude is proportional to the energy deposited in a tile calorimeter cell. After the shaper the signal is digitized every 25 ns, which is the LHC BC. The number of samples is programmable, however, typical values are 7 and 9 samples.

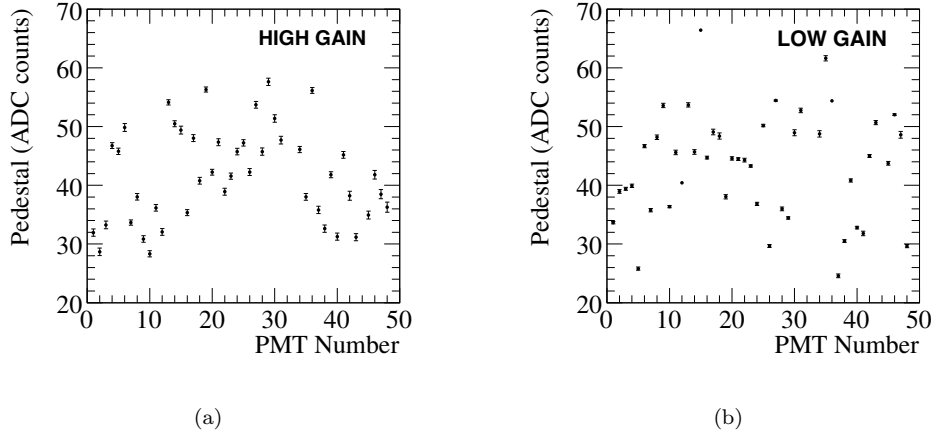
The final pulse and its digitized samples define three independent parameters: amplitude, phase and pedestal (see Figure 3.2). The pedestal is defined as the baseline of the signal. Typical values are between 30 and 60 ADC counts (see Figure 3.3), nevertheless this value is adjustable from the TileCal front-end electronics [40]. The phase is the time difference between the peak and the central



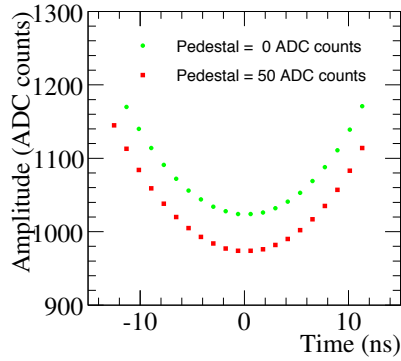
**Figure 3.2:** Definition of the amplitude, phase and pedestal of the TileCal digitized samples. The points corresponds to 9 samples taken every 25 ns.

sample, if the arriving time of the data is synchronized with the digitization clock the phase is fixed upon small variations. The amplitude is the most interesting parameter of the pulse because it is proportional to the energy deposited in a calorimeter cell. It is defined as the pulse height subtracting the pedestal. The amplitude values may vary between few negative ADC counts up to 1200 ADC counts before one of the samples saturates, this condition depends on the phase and on the pedestal level (see Figure 3.4).

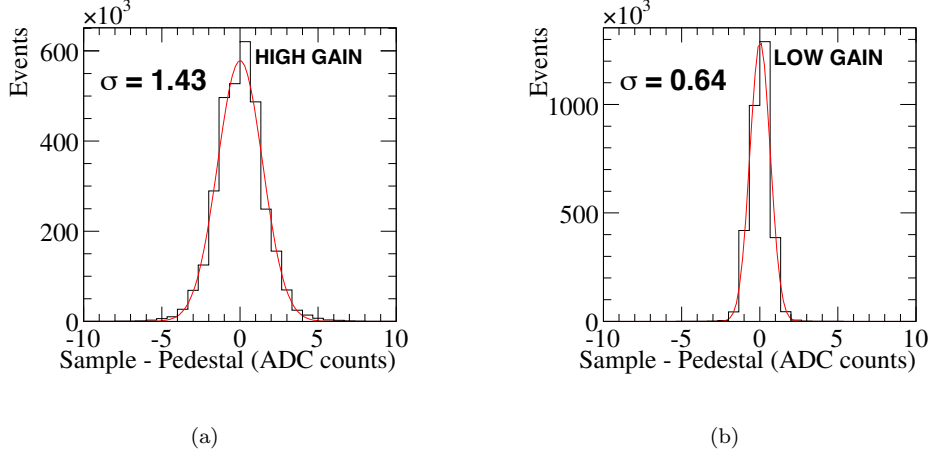
In the TileCal case, two sources of noise contribute to distort the signal: thermal noise and pile-up events. Thermal noise is mainly intrinsic to the electronics, it consists of small variations of the samples around their expected value. Figure 3.5 shows the distribution of the sample variations around the pedestal. In this case, the pedestal is calculated as the mean over all samples. For high gain the sigma of the distribution is around 1.4 ADC counts and for low gain 0.6 ADC counts which points out that the noise contribution is larger for high gain. On the contrary, the pile-up noise is due to uncorrelated events that are produced close in time to the event of interest and consequently they are piled-up with it, thus pile-up noise depends strongly on the LHC conditions. Since the number of collisions depends on the luminosity the pile-up noise also depends on this parameter increasing at



**Figure 3.3:** Distributions of the mean values of the pedestals for the 45 channels of the central barrel module A25 (run number 8770), for high gain (a) and low gain (b).



**Figure 3.4:** Maximum value of the amplitude before the saturation of at least one of the digitized samples as a function of the phase, for two different pedestal levels.



**Figure 3.5:** Histograms of the variation of the samples around the pedestal for the 45 channels of the central barrel module A25 (run number 8770), for high gain (a) and low gain (b). A Gaussian fit provides the sigma of noise in both distributions.

higher luminosities.

The reconstruction algorithms used in TileCal should be able to properly reconstruct the parameters of the signal (amplitude and phase). The contribution of the noise should be minimized in order to eliminate any bias on the reconstruction. The Optimal Filtering algorithm calculates the amplitude and phase by means of a weighted sum of the digitized samples, using weights that minimize the contribution of the noise [39, 41]. There exist two flavors of Optimal Filtering, OF1 and OF2. The difference between them is that OF1 reconstructs the amplitude and phase of the samples and estimates the pedestal as the first sample. On the contrary, OF2 calculates the amplitude, phase and pedestal as parameters of the reconstruction. The description of both algorithms is found in [38, 39], both algorithms have been studied and are implemented in the TileCal Read-Out Drivers for online processing of the data, however I focus here on the description of OF2 since it has been proved that it improves the energy resolution when only electronic noise is present [39].

Mathematically, the TileCal pulse before digitization can be expressed as:

$$S(t) = Ag(t - \tau) + p \quad \text{with} \quad t = t' + \tau_0 , \quad (3.1)$$

where  $g(t)$  is the pulse shape normalized in amplitude and with the peak at  $\tau_0$  which determines the time scale.  $A$  is the amplitude of the signal,  $\tau$  the relative phase and  $p$  the pedestal. After digitization we obtain  $n$  samples of the pulse every 25 ns,

$$S(t_i) = Ag(t_i - \tau) + p \quad \text{for} \quad i = 1, n . \quad (3.2)$$

At the LHC conditions, phase variations are expected to be small, therefore, a Taylor expansion can be applied in order to linearize the dependence with  $\tau$ :

$$S(t_i) \approx Ag(t_i) - A\tau g'(t_i) + p \quad \text{for} \quad i = 1, n , \quad (3.3)$$

and just for simplicity, the element at  $t_i$  can be re-written with the subindex  $i$  :

$$S_i \approx Ag_i - A\tau g'_i + p \quad \text{for} \quad i = 1, n . \quad (3.4)$$

So that,  $S_i$  represents the digitized sample at  $t_i$ , however, an additional term due to the noise contribution should also be included ( $n_i$ ):

$$S_i \approx Ag_i - A\tau g'_i + p + n_i \quad \text{for} \quad i = 1, n . \quad (3.5)$$

where by hypothesis  $\langle n_i \rangle = 0$  .

We can now define three quantities,  $u$ ,  $v$  and  $w$ , such as

$$u = \sum_{i=1}^n a_i S_i , \quad v = \sum_{i=1}^n b_i S_i \quad \text{and} \quad w = \sum_{i=1}^n c_i S_i , \quad (3.6)$$

and we require the expected value of these quantities to be equal to  $A$ ,  $A\tau$  and  $p$ ,

respectively:

$$\begin{aligned} A &= \langle u \rangle = \langle \sum_{i=1}^n a_i S_i \rangle = \sum_{i=1}^n a_i \langle S_i \rangle , \\ A\tau &= \langle v \rangle = \langle \sum_{i=1}^n b_i S_i \rangle = \sum_{i=1}^n b_i \langle S_i \rangle , \\ p &= \langle w \rangle = \langle \sum_{i=1}^n c_i S_i \rangle = \sum_{i=1}^n c_i \langle S_i \rangle . \end{aligned} \quad (3.7)$$

Combining Eq. 3.5 with Eq. 3.7 and imposing minimum variance of  $u$ ,  $v$  and  $w$  respect to  $A$ ,  $A\tau$  and  $p$  respectively we obtain a set of equations to calculate the optimal weights  $a_i$ ,  $b_i$  and  $c_i$ . Hence the  $n+3$  equations for the amplitude weights are:

$$\begin{aligned} \sum_{i=1}^n a_i g_i &= 1 , \\ \sum_{i=1}^n a_i g'_i &= 0 , \\ \sum_{i=1}^n a_i &= 0 , \\ \sum_{j=1}^n a_j R_{ij} - \lambda g_i - \kappa g'_i - \nu &= 0 \quad \text{for } i = 1, n , \end{aligned} \quad (3.8)$$

the  $n+3$  equations for the phase weights are:

$$\begin{aligned} \sum_{i=1}^n b_i g_i &= 0 , \\ \sum_{i=1}^n b_i g'_i &= -1 , \\ \sum_{i=1}^n b_i &= 0 , \\ \sum_{j=1}^n b_j R_{ij} - \mu g_i - \rho g'_i - \phi &= 0 \quad \text{for } i = 1, n , \end{aligned} \quad (3.9)$$

and the  $n+3$  equations for the pedestal weights are:

$$\begin{aligned} \sum_{i=1}^n c_i g_i &= 0 , \\ \sum_{i=1}^n c_i g'_i &= 0 , \\ \sum_{i=1}^n c_i &= 1 , \\ \sum_{j=1}^n c_j R_{ij} - \alpha g_i - \beta g'_i - \gamma &= 0 \quad \text{for } i = 1, n , \end{aligned} \quad (3.10)$$

where  $\lambda$ ,  $\kappa$ ,  $\nu$ ,  $\mu$ ,  $\rho$ ,  $\phi$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  are the Lagrange multipliers and  $R_{ij}$  represents

the element  $ij$  of the noise autocorrelation matrix defined as:

$$R_{ij} = \frac{\sum (n_i - \langle n_i \rangle) (n_j - \langle n_j \rangle)}{\sqrt{\sum (n_i - \langle n_i \rangle)^2 \sum (n_j - \langle n_j \rangle)^2}} . \quad (3.11)$$

Solving the systems defined in Eq. 3.8, 3.9 and 3.10 we can calculate the weights and reconstruct  $A$ ,  $A\tau$  and  $p$  as:

$$A = \sum_{i=1}^n a_i S_i , \quad A\tau = \sum_{i=1}^n b_i S_i \quad \text{and} \quad p = \sum_{i=1}^n c_i S_i . \quad (3.12)$$

Moreover, Optimal Filtering allows to calculate a quality factor defined as

$$Q_F = \sum_{i=1}^n |S_i - (Ag_i + p)| . \quad (3.13)$$

The quality factor provides information about the goodness of the reconstruction. This information can be used online to decide to send raw data or the reconstruction result but it could also be useful for deciding when to ask for calibration runs.

Optimal Filtering has been chosen to reconstruct in real time the amplitude and phase of the TileCal pulses inside the RODs. The ROD DSPs require an accurate and simple algorithm in order to provide the reconstructed parameters to the ATLAS general data acquisition system and the 2nd level trigger in less than 10  $\mu$ s, however for the offline reconstruction a more complex algorithm has been selected, the so-called FIT method. FIT also calculates the amplitude, phase and pedestal of the digitized pulse minimizing the  $\chi^2$  defined as:

$$\chi^2 = \sum_{i=1}^n \left\{ \frac{S_i - (Ag_i - A\tau g'_i + p)}{\sigma_i} \right\}^2 , \quad (3.14)$$

where  $\sigma_i$  is the standard deviation of the noise at time  $t_i$ . The value of  $\sigma_i$  corresponds to the sigma of the distributions shown in Figure 3.5. The conditions to

minimize the  $\chi^2$  are

$$\frac{\partial \chi^2}{\partial A} = 0, \quad \frac{\partial \chi^2}{\partial A\tau} = 0 \quad \text{and} \quad \frac{\partial \chi^2}{\partial p} = 0, \quad (3.15)$$

solving the system in Eq. 3.15 we obtain

$$A = \frac{(\Delta_{Sg}\Delta_{g'g'} - \Delta_{Sg'}\Delta_{gg'})}{\Delta_g}, \quad A\tau = \frac{(\Delta_{Sg}\Delta_{gg'} - \Delta_{Sg'}\Delta_{gg})}{\Delta_g}, \quad (3.16)$$

$$p = \frac{1}{\Sigma} \left\{ \Sigma_S - \frac{(\Delta_{Sg}\Delta_{g'g'} - \Delta_{Sg'}\Delta_{gg'})\Sigma_g + (\Delta_{Sg}\Delta_{gg'} - \Delta_{Sg'}\Delta_{gg})\Sigma_{g'}}{\Delta_g} \right\} \quad (3.17)$$

where

$$\begin{aligned} \Delta_g &= \Delta_{gg}\Delta_{g'g'} - \Delta_{gg'}\Delta_{gg'}, & \Delta_{gg} &= \Sigma_{gg} - \frac{1}{\Sigma}\Sigma_g\Sigma_g, & \Delta_{gg'} &= \Sigma_{gg'} - \frac{1}{\Sigma}\Sigma_g\Sigma_{g'}, \\ \Delta_{g'g'} &= \Sigma_{g'g'} - \frac{1}{\Sigma}\Sigma_{g'}\Sigma_{g'}, & \Delta_{Sg} &= \Sigma_{Sg} - \frac{1}{\Sigma}\Sigma_S\Sigma_g, & \Delta_{Sg'} &= \Sigma_{Sg'} - \frac{1}{\Sigma}\Sigma_S\Sigma_{g'}, \\ \Sigma_{gg} &= \sum_{i=1}^n g_i g_i / \sigma_i^2, & \Sigma_{gg'} &= \sum_{i=1}^n g_i g'_i / \sigma_i^2, & \Sigma_{g'g'} &= \sum_{i=1}^n g'_i g'_i / \sigma_i^2, \\ \Sigma_g &= \sum_{i=1}^n g_i / \sigma_i^2, & \Sigma_{g'} &= \sum_{i=1}^n g'_i / \sigma_i^2, & \Sigma_S &= \sum_{i=1}^n S_i / \sigma_i^2, \\ \Sigma_{Sg} &= \sum_{i=1}^n S_i g_i / \sigma_i^2, & \Sigma_{Sg'} &= \sum_{i=1}^n S_i g'_i / \sigma_i^2, & \Sigma &= \sum_{i=1}^n 1 / \sigma_i^2. \end{aligned} \quad (3.18)$$

The equations used by FIT to calculate the three parameters of the pulse are much more complicated than the ones used by Optimal Filtering. For this reason FIT is not suitable to run inside the ROD DSPs. Nevertheless, data acquired during testbeam and commissioning periods, thus the calibration constants, have been reconstructed using the FIT method. Since both FIT and OF should provide the same result and FIT has been studied over the past years, it is taken as a reference for validating the Optimal Filtering algorithm.

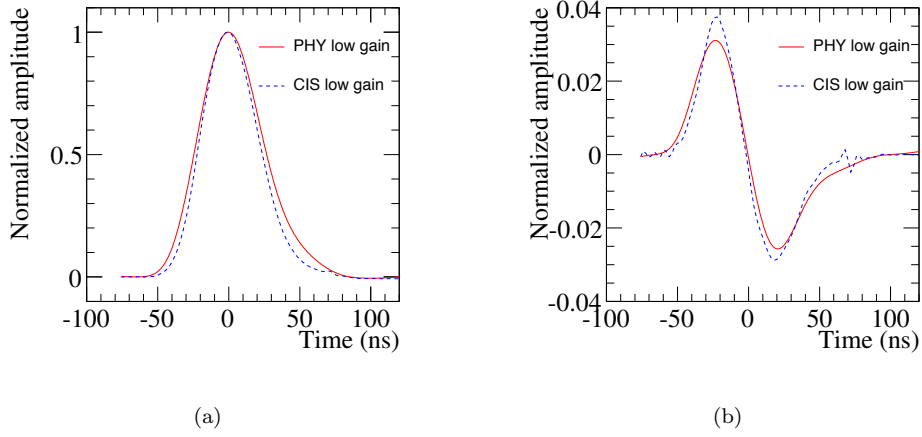


### 3.2.2 Calculation of the Optimal Filtering weights

Optimal Filtering weights are calculated from the pulse shape, its derivative and the noise autocorrelation matrix. Afterward, the systems from Eq. 3.8, 3.9 and 3.10, resulting from the minimization of the noise contribution, should be solved.

TileCal pulse shapes and their derivatives can be found inside the ATLAS general software. For this analysis we have used the pulse shapes stored in the ATLAS release 13.0.10, under the TileConditions package. There exist different pulse shapes for several types of runs, physics, charge injection (CIS) and laser, and they are different for high and low gain. There are also small channel to channel variations (less than 1%), however during testbeam and commissioning the same pulse shape for all the channels has been used. The way of calculating the pulse shape depends on the type of run. In order to calculate the CIS pulse, it is possible to inject the same charge over several events at different phases. However, the calculation of the pulse shape for physics is more complicated [42]. Real data from testbeam is used and since the beam is asynchronous a sweep of different phases is also achieved but with different amplitudes. In order to get the final pulse it is needed to normalize and combine the signals from different amplitudes and channels.

The reconstruction with Optimal Filtering depends strongly on the pulse shape used. Figure 3.6 shows the pulse shapes and their derivatives (only for low gain) for physics and charge injection runs. Notice that pulses for physics are 10% larger on area than charge injection pulses. The number of points and the time range on the pulses is variable. In current data we are using pulses for physics calculated between -75.5 ns and 124.5 ns in steps of 0.5 ns and pulses for charge injection and laser calculated between -76 ns and 122 ns in steps of 2 ns, being the time origin at the pulse maximum for the pulse shape and when the derivative crosses zero for the derivative pulse. For a given initial phase  $\tau_0$ , the  $g(t_i)$  and  $g'(t_i)$  are extracted from this data using a linear interpolation, and values out of the time range are



**Figure 3.6:** Pulse shape for physics and charge injection runs (a) and their derivative (b).

set to the nearest value,

$$t_i = t'_i + \tau_0 = 25(i_c - i) + \tau_0 \quad \text{for } i = 1, n, \quad (3.19)$$

where  $i_c$  is the position of the central sample.

To complete the calculation of the Optimal Filtering weights the noise autocorrelation matrix is also needed, however, for testbeam and commissioning the noise contribution is mainly due to the TileCal electronics. It has been observed that TileCal samples are weakly correlated during testbeam and commissioning, and the best choice in this case is to use the Unitary matrix [39]. Figure 3.7 shows the OF weights for OF2 used to calculate the amplitude (a), phase (b) and pedestal (c) of the signal for the first, middle and last sample as function of the initial phase  $\tau_0$ . The OF weights for the amplitude follow a similar tendency as the pulse shape values, in this way the largest weights are applied to the largest samples, and the samples with low signal contribution are weighted by the smallest OF weights. The OF weights for the phase calculation follow the tendency of the derivative

of the pulse, changing the sign of the OF weights in the two sides of the peak. Finally, the OF weights to calculate the pedestal follow the inverse distribution of the pulse shape giving more importance to the samples far from the peak.

### 3.2.3 Iterative procedure

A good reconstruction is obtained with the Optimal Filtering using Eq. 3.12 if it is applied to events with fixed phase upon small variations, this occurs in the LHC however this does not occur during the testbeam and commissioning. During the testbeam the beam is asynchronous and thus the phase of the samples suffers from large event to event variations. The same occurs during the commissioning where cosmic muons impinge the calorimeter asynchronously. In this case, Optimal Filtering can still be applied and it is possible to obtain an accurate reconstruction incorporating an iteration procedure. This procedure increases the processing time but improves considerably the reconstruction. Even though the processing time limit for the LHC is 10  $\mu$ s, for the testbeam and commissioning the limit on the processing time is not a constraint since the trigger frequency hardly exceeds the 1 kHz during testbeam and the 50 Hz during commissioning.

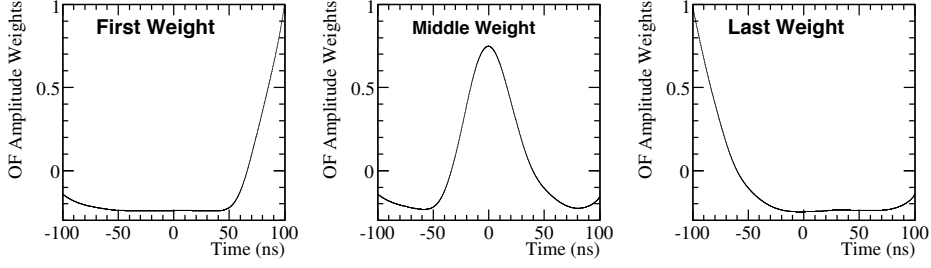
The iteration procedure consists of a first estimation of the initial phase that ascertains the index of the maximum sample. If the maximum sample is the central sample, the first iteration begins with OF weights calculated for

$$\tau_0 = 0 \text{ ns} , \quad (3.20)$$

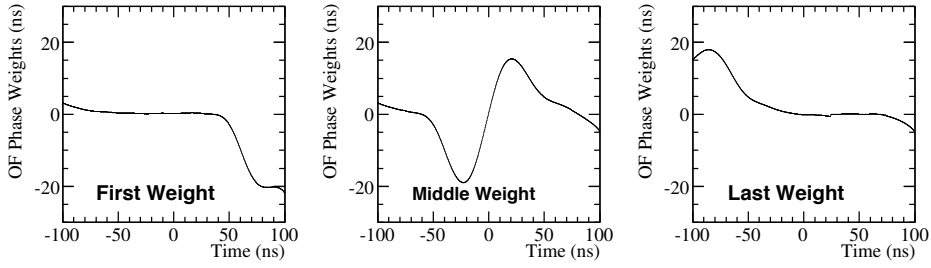
while, if the maximum sample differs from the central sample, the weights are calculated for

$$\tau_0 = 25(i_c - i_{\max}) \text{ ns} , \quad (3.21)$$

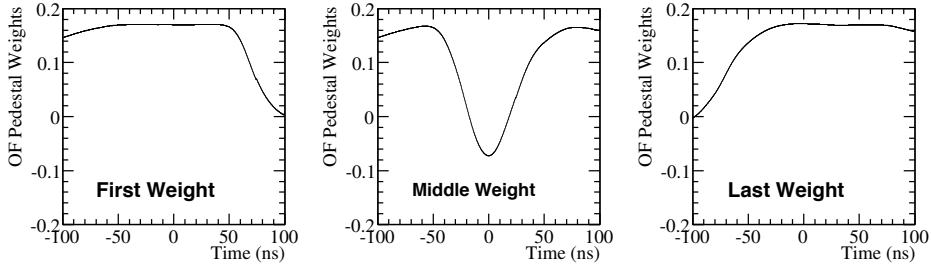
being  $i_{\max}$  and  $i_c$  the index of the maximum sample and the central sample respectively.



(a)



(b)



(c)

**Figure 3.7:** Optimal Filtering weights (OF2), for physics, to calculate the amplitude (a), the phase (b) and the pedestal (c) of the signal for first, middle and last sample.

Afterward the amplitude, phase and pedestal are calculated in each iteration as:

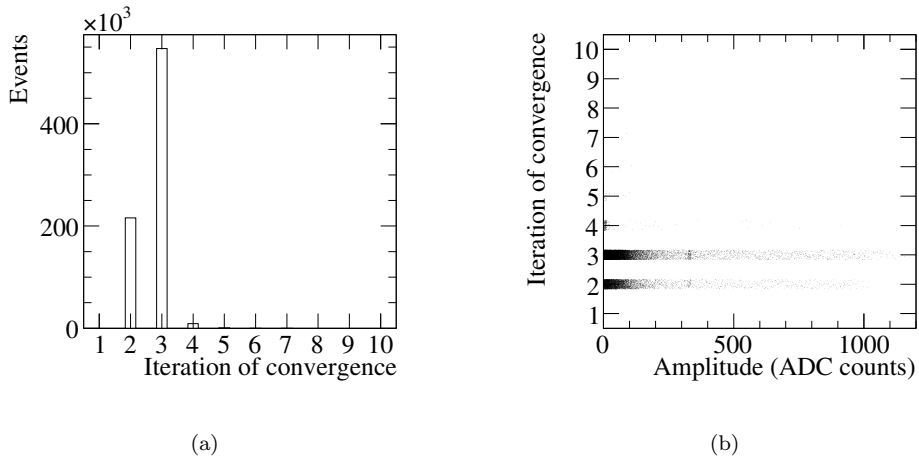
$$A_k = \sum_{i=1}^n a_i \Big|_{\tau_{k-1}} S_i , \quad (3.22)$$

$$\tau_k = \frac{1}{A_k} \sum_{i=1}^n b_i \Big|_{\tau_{k-1}} S_i , \quad (3.23)$$

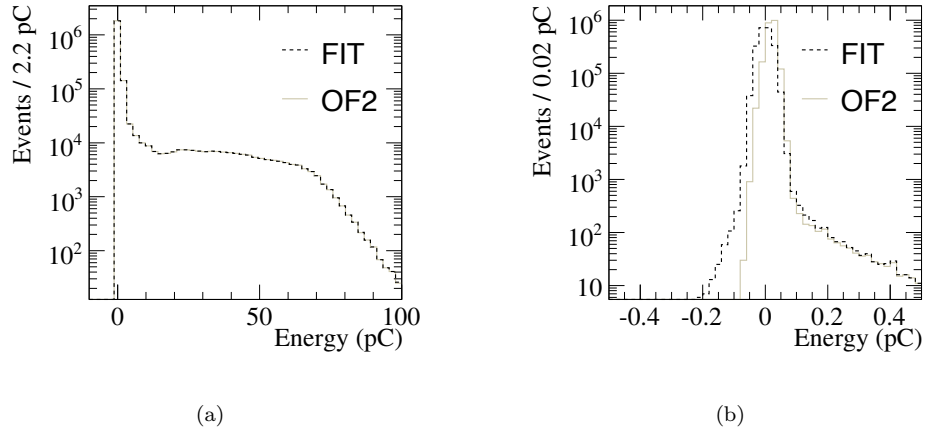
$$p_k = \sum_{i=1}^n c_i \Big|_{\tau_{k-1}} S_i , \quad (3.24)$$

where  $k$  is the iteration index starting from 1. It has been observed that the amplitude converges within three iterations for Optimal Filtering weights calculated in steps of 1 ns. Figure 3.8(a) shows the number of iterations needed to obtain convergence of the amplitude better than 1% and Figure 3.8(b) shows the dependence of the number of iterations needed to converge as function of the reconstructed amplitude. The data used in these plots corresponds to a physics run from the testbeam of July 2003, where pions at 180 GeV impinge the calorimeter at  $\eta = 0.35$  (run number 340427).

This iterative procedure provides an accurate value of the amplitude for cells with large signal. However, for cells where there is not energy deposited, thus the amplitude is close to zero, an effect that overestimates the amplitude appears. Figure 3.9(a) shows the distribution of the energy calculated with FIT (dashed line) and with Optimal Filtering (solid line) for all the cells within a module where pions collide at 180 GeV, a good agreement between FIT and OF reconstruction is observed. Figure 3.9(b) shows the reconstructed energy for all the cells within a module without signal, where there is only electronic noise contribution, notice that the iteration procedure has shifted the OF distribution of the amplitude to positive values therefore the noise distribution is not peaked at zero as it is the case for the FIT distribution. This occurs because the first guess of the initial phase  $\tau_0$  is to assume that the maximum sample corresponds to the peak. Thus in the first iteration the largest OF weight is always applied to the maximum sample. If



**Figure 3.8:** (a) Histogram of the number of iterations needed to obtain a convergence of the amplitude better than 1%. (b) Histogram of the number of iterations needed to converge the amplitude versus the reconstructed amplitude, data corresponds to pions at 180 GeV (run number 340427).



**Figure 3.9:** Energy distribution for all the cell within a TileCal barrel module with pions at 180 GeV impinging (a) and with only electronic noise (b) (run number 340427).

there is some signal contribution the peak will be near the maximum sample and the assumption is correct, however, if there is no signal contribution (only noise contribution) the largest OF weight will be still applied to the maximum sample, which is the one with the largest positive deviation from the mean. Consequently, the amplitude is always larger than it is expected and the pedestal distribution is biased to positive values. In order to avoid this effect the reconstruction algorithm should identify the events without signal and apply a different procedure.

### 3.2.4 Signal and Pedestal identification

In order to identify the pedestal we study first the distribution of the samples. Figure 3.10 shows the distributions of the absolute difference between the maximum sample and the first sample (left) and the minimum sample and the first sample (right), for pions at 180 GeV (a, b, c and d) and cosmic muons (e and f). The dashed line represents a cut on this difference of  $3\sigma_{\text{noise}}$ . The first sample is taken as a stable reference of the pedestal because it is usually placed near the

pulse tail. For that reason, even when there are large signals the first sample is the closest value of the pedestal. Consequently, the cut to identify signal events consists of requiring

$$S_{\max} - S_1 > 3\sigma_{\text{noise}} \quad , \quad (3.25)$$

being  $S_{\max}$  and  $S_1$  the maximum sample and the first sample respectively and  $\sigma_{\text{noise}}$  the sigma of the noise distribution shown in Figure 3.5. However in special cases where the phase is very large, for signal events, the first sample can contain a large signal contribution and the previous condition will be not fulfilled. In order to avoid this the event will also be considered as a signal event if

$$S_1 - S_9 > 12\sigma_{\text{noise}} \quad , \quad (3.26)$$

being  $S_9$  the last sample. Using these cuts there are still some pedestal events identified as signal events that will continue biasing the distribution to positive amplitudes. In order to compensate this an equivalent shift to negative values is applied to the event if

$$S_1 - S_{\min} > 3\sigma_{\text{noise}} \quad , \quad (3.27)$$

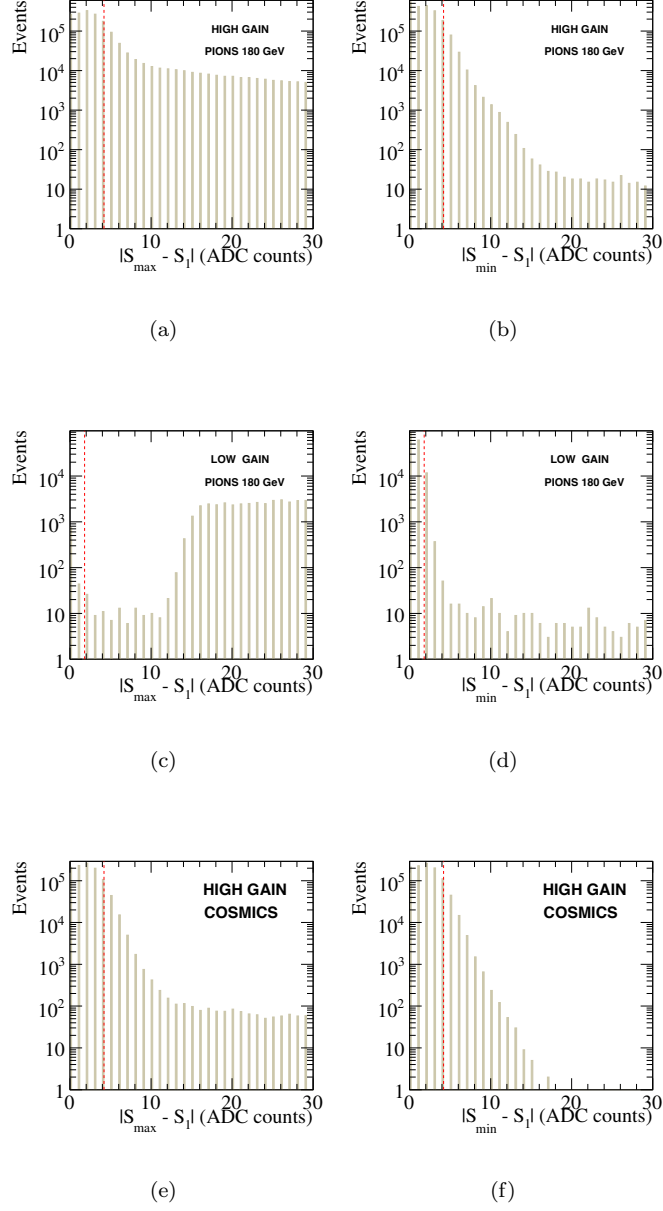
with  $S_{\min}$  being the minimum sample.

If condition in Eq. 3.25 or in Eq. 3.26 is fulfilled the Optimal Filtering algorithm is applied with the usual iteration procedure (named positive iterations):

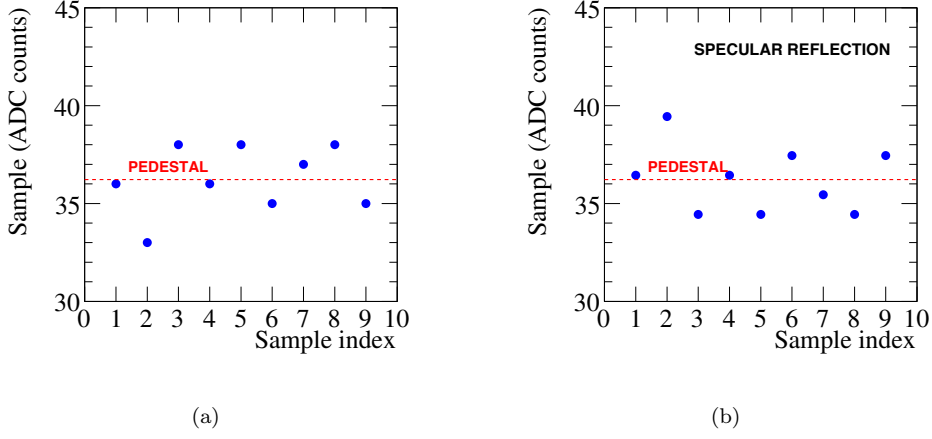
$$A_k = \sum_{i=1}^n a_i \Big|_{\tau_{k-1}} S_i \quad , \quad (3.28)$$

$$\tau_k = \frac{1}{A_k} \sum_{i=1}^n b_i \Big|_{\tau_{k-1}} S_i \quad , \quad (3.29)$$





**Figure 3.10:** Histogram of the absolute difference between the maximum sample  $S_{\max}$  and the first sample  $S_1$  (on the left) and between the minimum sample  $S_{\min}$  and the first sample (on the right), for pions at 180 GeV, high and low gain, (a, b, c and d) and for cosmic muons (e and f).



**Figure 3.11:** Distribution of the samples from a pedestal event (a) and their specular reflection (b), the mean of the samples is taken as the pedestal.

$$p_k = \sum_{i=1}^n c_i \Big|_{\tau_{k-1}} S_i , \quad (3.30)$$

being  $\tau_0 = 25(i_c - i_{\max})$  and  $k$  runs from 1 to 3. On the contrary, if Eq. 3.25 and Eq. 3.26 are not fulfilled but Eq. 3.27 is fulfilled, the Optimal Filtering algorithm is applied to the specular reflection of the samples around the pedestal, so the maximum sample is converted to the minimum sample and vice versa (see Figure 3.11):

$$S_i \rightarrow S'_i = 2p - S_i . \quad (3.31)$$

For the amplitude and phase this is equivalent to apply the OF algorithm with iterations to the samples with opposite sign (named negative iterations) while for

the pedestal we can still use the original samples:

$$A_k = \sum_{i=1}^n a_i \Big|_{\tau_{k-1}} (-S_i) , \quad (3.32)$$

$$\tau_k = \frac{1}{A_k} \sum_{i=1}^n b_i \Big|_{\tau_{k-1}} (-S_i) , \quad (3.33)$$

$$p_k = \sum_{i=1}^n c_i \Big|_{\tau_{k-1}} S_i . \quad (3.34)$$

Notice now that the initial phase  $\tau_0$  is calculated from the minimum sample

$$\tau_0 = 25(i_c - i_{\min}) . \quad (3.35)$$

The final amplitude is the result from the negative iteration procedure with opposite sign while the phase and the pedestal remains the same.

The events that do not fulfill either of the three conditions (Eq. 3.25, Eq. 3.26 or Eq. 3.27) are tagged as standard pedestal events and reconstructed without iterations, using OF weights calculated at  $\tau_0 = 0$ ,

$$A = \sum_{i=1}^n a_i \Big|_{\tau_0=0} S_i , \quad (3.36)$$

$$\tau = \frac{1}{A} \sum_{i=1}^n b_i \Big|_{\tau_0=0} S_i , \quad (3.37)$$

$$p = \sum_{i=1}^n c_i \Big|_{\tau_0=0} S_i . \quad (3.38)$$

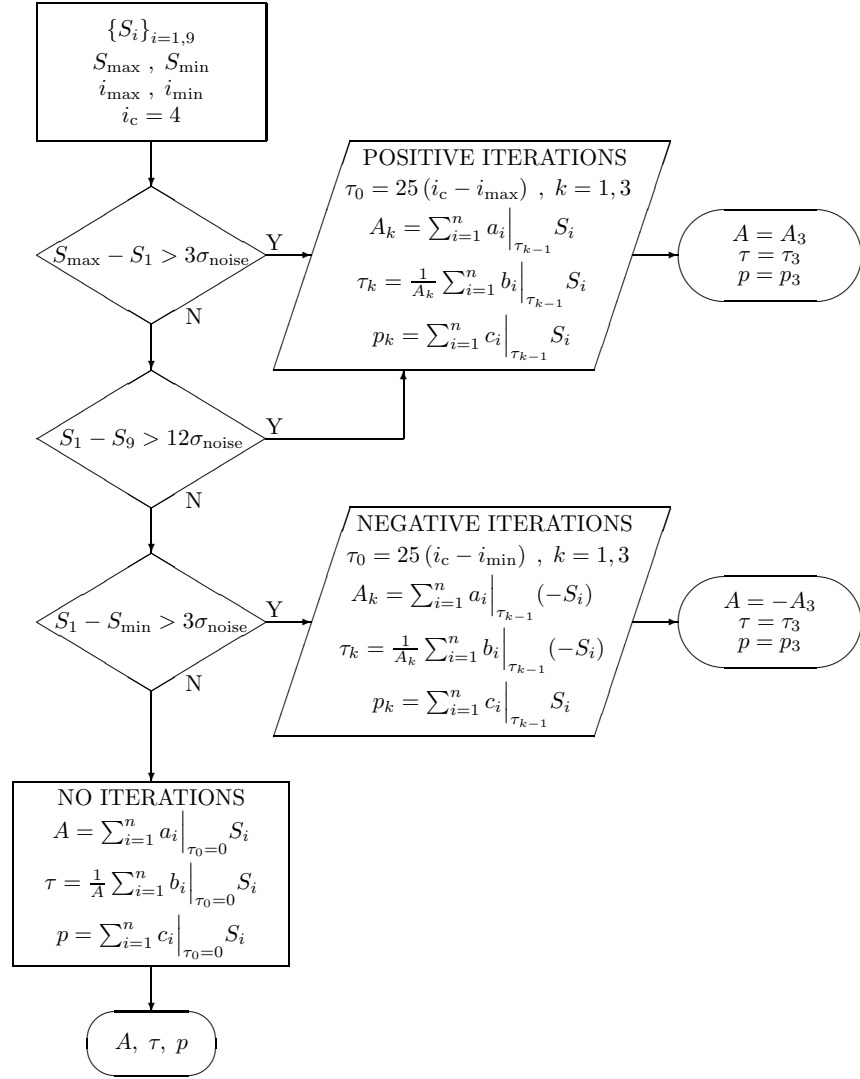
Figure 3.12 shows a chart flow of the algorithm and Figure 3.13 shows the final reconstruction with Optimal Filtering of a module without signal. The events that fulfill the cut in Eq. 3.27 are shown in Figure 3.13(a), notice that the distribution is now peaked to negative values. Figure 3.13(b) shows reconstruction without iterations for events tagged as standard pedestal and finally Figure 3.13(c) shows the reconstruction for events that fulfill the cuts defined in Eq. 3.25 or Eq. 3.26. In this distribution we observe a small tail to positive values due to few low energy depositions. The merging of these three distributions give us the total contribution which is compared with the FIT reconstruction in Figure 3.14. The peak of the pedestal distribution is now centered at zero as the FIT distribution, moreover, the reconstruction using Optimal Filtering provides a thinner peak which deals to a better energy resolution.

### 3.2.5 Optimal Filtering and FIT comparison

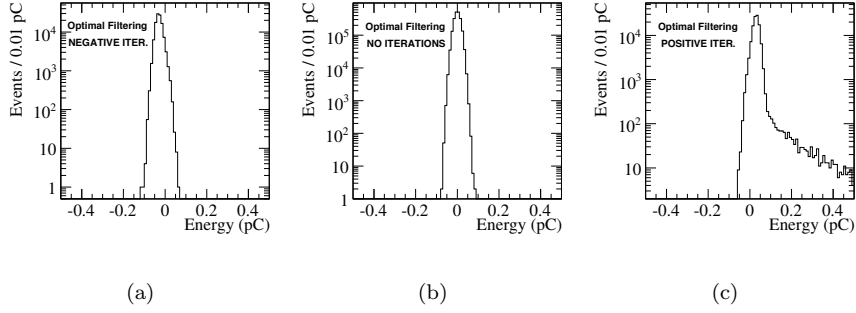
The Optimal Filtering and the FIT method have been applied to testbeam and commissioning data making use of the iteration mechanism and the pedestal identification. Figure 3.15 shows the distribution of the energy deposited by pions at 180 GeV in the Tile Calorimeter, reconstructed with OF (a) and with FIT (b). This energy has been calculated as the sum of all the channels, with signal over a threshold, from all the drawers at the testbeam setup, a detailed description of these cuts is in [39] and in Table 3.1. A Gaussian fit at  $3\sigma$  is used to obtain the sigma and the mean of the energy distributions (a and b), both algorithms, OF and FIT, provide the same resolution:

$$\frac{E}{\Delta E} = 6.02 \pm 0.06 \% . \quad (3.39)$$

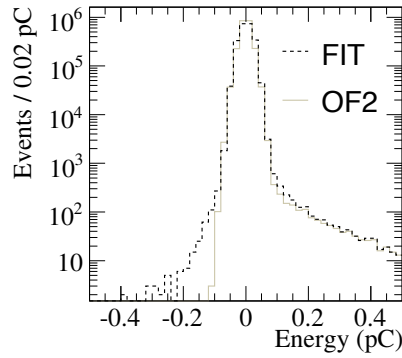
Notice that the energy in Figure 3.15 is in pC, however, the amplitude resulting from the reconstruction is in ADC counts. Since calibration constants are calculated for the FIT method the same are applied to the Optimal Filtering reconstruction with satisfactorily results. Although in a future it would be convenient to calculate specific calibration constants for the Optimal Filtering algorithm.



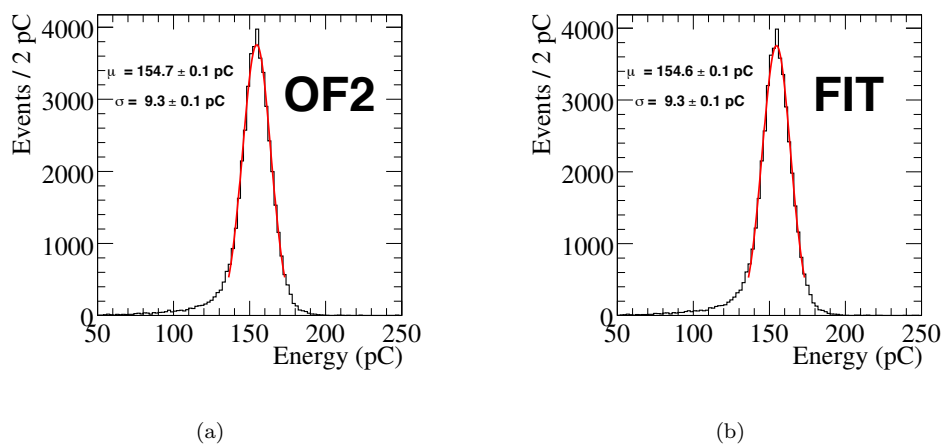
**Figure 3.12:** Flow chart of the Optimal Filtering algorithm including iterations and identification of pedestal events.



**Figure 3.13:** Distributions of the amplitude reconstructed using Optimal Filtering with negative iterations (a), without iterations (b) and with positive iterations (c), for a module without signal (run number 340427).



**Figure 3.14:** Histogram of the amplitude reconstruction using Optimal Filtering (OF2) and FIT for a module without signal (run number 340427).



**Figure 3.15:** Histograms of the energy deposited by pions at 180 GeV from the testbeam of July 2003, impinging into a tile calorimeter module at  $\eta = 0.35$ , (a) reconstructed with the Optimal Filtering algorithm and (b) with the FIT method. A Gaussian fit has been applied to obtain the mean and the sigma of both distributions.

**Table 3.1:** Cuts applied to the pion reconstruction.

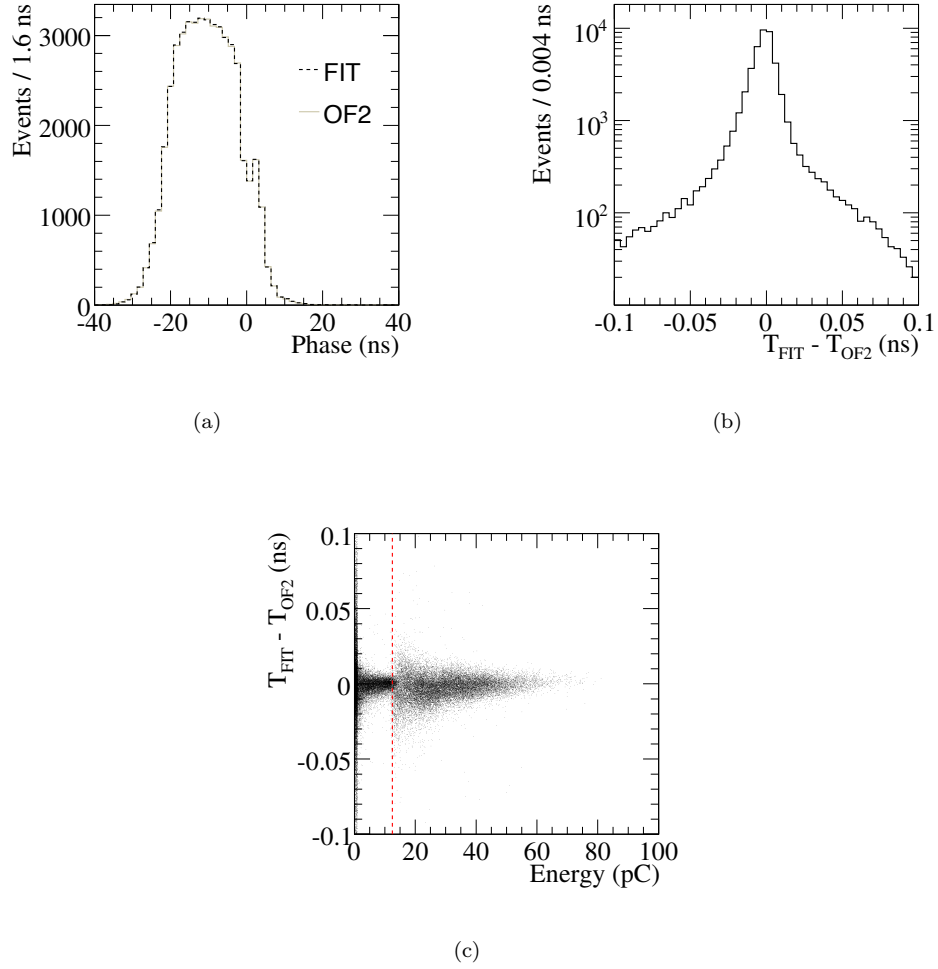
| CUTS   | Description                                                          |
|--------|----------------------------------------------------------------------|
| CUT1 : | X and Y coordinates of the beam chambers 1 and 2 between $\pm 25$ mm |
| CUT2 : | Select physics trigger (Trig = 1)                                    |
| CUT5:  | At least one channel with signal larger than 1 pC                    |
| CUT6:  | Sum all the channels with signal above 0.07 pC                       |

The run analyzed from the testbeam contains pions that collide to the positive side of a central barrel module at  $\eta = 0.35$ . The energy is then deposited preferentially in cell A4 (PMT 16 and 19), cell BC4 (PMT 17 and 18) and cell D2 (PMT 27 and 28). Figure 3.16(a) shows the distribution of the phase reconstructed with FIT (dashed line) and with OF2 (solid line) of the PMT 16 which corresponds to cell A4. Since the beam is asynchronous we observe a spread distribution with a width around 25 ns. In Figure 3.16(b) it is plotted the difference between the FIT phase reconstruction and the OF2 phase reconstruction, in most of the cases the difference is below  $\pm 0.05$  ns, since the phase is divided by the amplitude at low energies the resolution gets worse and the difference rises, see in Figure 3.16(c) the distribution of the difference on the phase reconstruction versus the amplitude in pC. The dashed line at 12.5 pC divides the space for high gain (left) and low gain (right).

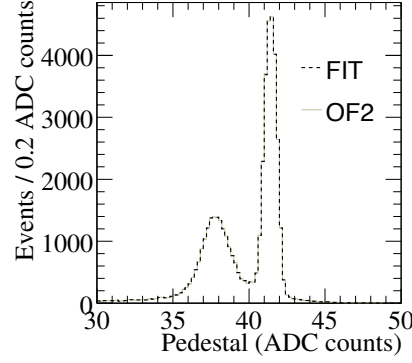
The baseline of the pulse is also calculated with the Optimal Filtering and the FIT method. Figure 3.17 shows the pedestal distribution of the PMT 16 reconstructed using OF2 (solid line) and using FIT (dashed line). The two peaks with mean value of 38 ADC counts and of 41.5 ADC counts represent the pedestal for high and low gain respectively.

The quality factor defined in Eq. 3.13 provides a test of the goodness of the reconstruction. Figure 3.18(a) shows the histogram of the quality factor for the Optimal Filtering reconstruction of the signal collected by the PMT 16. The dark area represents all the events while the light area represents the events with low gain, which are events with deposited energies larger than 12.5 pC. Notice





**Figure 3.16:** (a) Histogram of the phase reconstructed with Optimal Filtering, OF2, (solid line) and with FIT (dashed line) for the PMT 16 of central barrel module. (b) Distribution of the differences between the phase reconstructed with FIT and the phase reconstructed with OF. (c) Distribution of the difference between FIT and OF phase versus the energy in pC reconstructed with FIT.



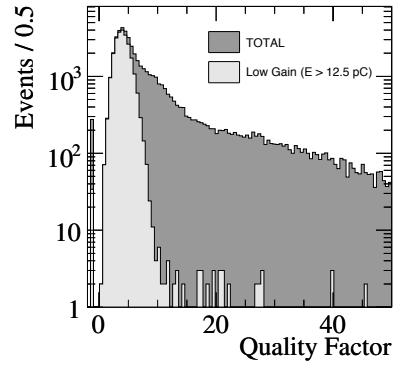
**Figure 3.17:** Histogram of the pedestal reconstructed with Optimal Filtering, OF2, (solid line) and with FIT (dashed line).

the peak at -1 which corresponds to the events tagged as standard pedestal and therefore reconstructed without iterations. Figure 3.18(b) and 3.18(c) show the quality factor as function of the energy in pC reconstructed with OF2 and FIT respectively, although the definitions of the quality factor are different (see Eq. 3.13 and Eq. 3.14) both algorithms show the same behavior, increasing the quality factor at increasing energies.

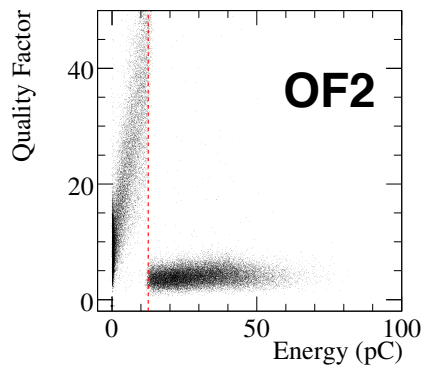
### 3.3 Optimal Filtering implementation in the ROD DSPs

#### 3.3.1 Optimal Filtering weights in fixed-point format

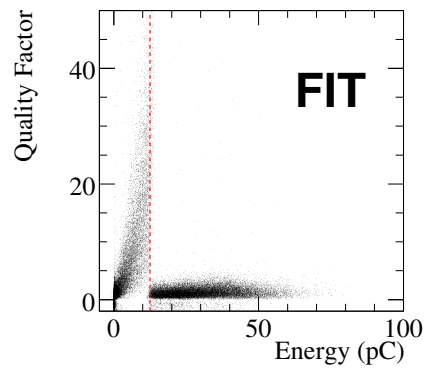
Digital signal processors usually have certain limitations concerning the type of instructions they can implement, the data type and the amount of memory available. The TMS320C6414 DSP from Texas Instruments is a fixed-point processor with a cycle rate of 720 MHz, implementing up to eight 32-bit instructions per cycle. It is provided with six ALUs and two multiplier units that enhance the implementation of MAC instructions. The memory is divided into a level-one



(a)



(b)



(c)

**Figure 3.18:** (a) Histogram of the quality factor of the reconstruction using Optimal Filtering, for all events (in dark) and for events with deposited energy larger than 1 pC (in light). (b) Distribution of the quality factor from OF2 versus the energy in pC reconstructed with OF. (c) Distribution of the quality factor from FIT versus the energy in pC reconstructed with FIT.

cache of 32 kB (half for data and half for program cache) and a level-two cache of 1024 kB.

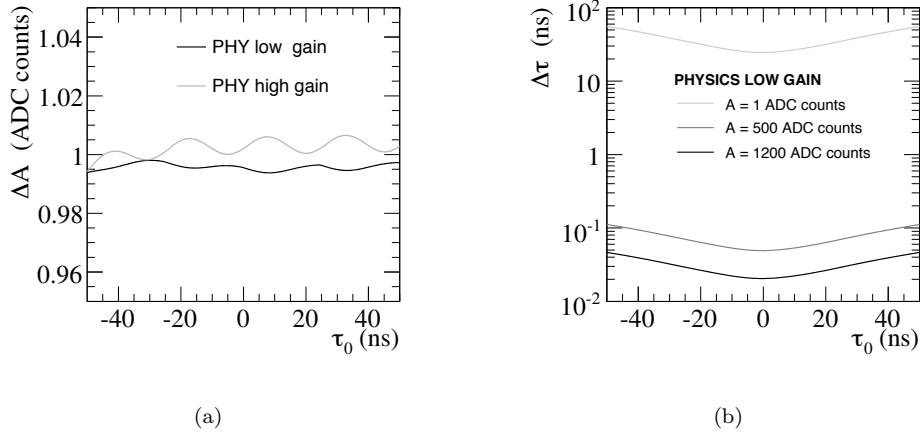
Optimal Filtering is a suitable algorithm for the Tile ROD DSPs [38] because it calculates the amplitude and the phase of a digitized signal by means of a weighted sum of its digitized samples. The OF weights are calculated offline using calibration data and are converted to fixed-point numbers before being uploaded to the ROD DSPs. The minimum number of bits required for the fixed-point representation of the OF weights should be such that its precision does not affect the calorimeter energy and phase reconstruction. The precision of a fixed-point number is defined as the difference between two consecutive values, thus it is  $2^{-m}$ , being  $m$  the number of fractional bits. Suppose that we have infinite precision on the calculation of the OF weights, then only the samples contribute to the uncertainties on the amplitude and phase. For uncorrelated samples (as it is the case for commissioning and testbeam) the uncertainties are given by:

$$\Delta A = \sqrt{\sum_{i=1}^n \left( \frac{\partial A}{\partial S_i} \Delta S_i \right)^2} \quad \text{and} \quad \Delta \tau = \sqrt{\sum_{i=1}^n \left( \frac{\partial \tau}{\partial S_i} \Delta S_i \right)^2 + \left( \frac{\partial \tau}{\partial A} \Delta A \right)^2} . \quad (3.40)$$

Since the samples are integer numbers (there are not fractional bits) its precision is 1 ADC count ( $\Delta S_i = 1$ ) and using Eq. 3.12 the uncertainties on the amplitude and phase become

$$\Delta A = \sqrt{\sum_{i=1}^n a_i^2} \quad \text{and} \quad \Delta \tau = \frac{1}{A} \sqrt{(\tau \Delta A)^2 + \sum_{i=1}^n b_i^2} . \quad (3.41)$$

As the weights depend on the initial phase ( $\tau_0$ ) the uncertainties of the amplitude and phase also depend on this initial phase. Figure 3.19(a) shows the uncertainty on the amplitude versus the initial phase for high and low gain physics events. For phases within  $\pm 50$  ns the uncertainty on the amplitude is around 1 ADC count for high and low gain and using OF2 weights. Figure 3.19(b) shows the uncertainty on the phase versus the initial phase for low gain and different values of the amplitude



**Figure 3.19:** (a) Uncertainty of the amplitude versus the initial phase  $\tau_0$  for low and high gain physics events using OF2 weights. (b) Uncertainty of the phase versus the initial phase for low gain physics events and different values of the amplitude using OF2 weights.

using OF2 weights. We observe that the uncertainty on the phase depends strongly on the amplitude and as the amplitude decreases the phase uncertainty increases, becoming not reliable for amplitudes very close to zero.

The precision on the samples sets an uncertainty on the amplitude of around 1 ADC count, considering now the contribution of the OF weights precision, the uncertainty on the amplitude is given by

$$\Delta A = \sqrt{\sum_{i=1}^n \left( \frac{\partial A}{\partial S_i} \Delta S_i \right)^2 + \sum_{i=1}^n \left( \frac{\partial A}{\partial a_i} \Delta a_i \right)^2} . \quad (3.42)$$

The precision on the samples is set again to 1 ADC count and the precision of the OF weights is fixed by the number of fractional bits ( $x$ ) of their fixed-point representation, making  $\Delta a_i = 2^{-x}$ . Therefore, the precision on the amplitude is

given by

$$\Delta A = \sqrt{\sum_{i=1}^n a_i^2 + \sum_{i=1}^n (S_i 2^{-x})^2} \quad . \quad (3.43)$$

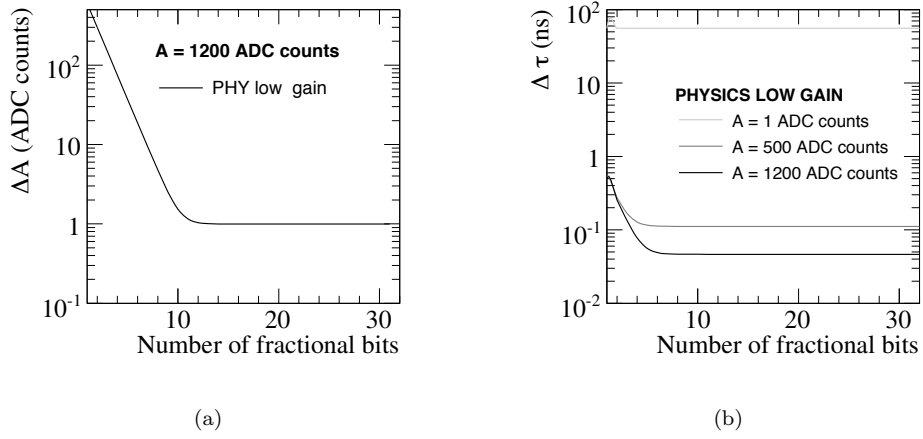
Figure 3.20(a) shows the uncertainty on the amplitude ( $\Delta A$ ) including OF weights precision as a function of the number of fractional bits ( $x$ ) used for those weights. The samples correspond to an amplitude of 1200 ADC counts, which is when the contribution of the OF weights error is larger, and an initial phase equal to 0 ns. The figure indicates that 10 bits for fractional part is sufficient for the amplitude OF weights precision.

The same procedure applies to the phase, where the uncertainty is given by

$$\Delta \tau = \frac{1}{A} \sqrt{(\tau \Delta A)^2 + \sum_{i=1}^n b_i^2 + \sum_{i=1}^n (S_i 2^{-y})^2} \quad , \quad (3.44)$$

being  $y$  the number of fractional bits for the fixed-point representation of the phase weights. Figure 3.20(b) shows the uncertainty of the phase,  $\Delta \tau$ , as a function of  $y$ , at least five fractional bits are needed to get a precision better than 0.1 ns on the calculation of the phase for an amplitude of 1200 ADC counts.

We conclude that a minimum of 10 bits and 5 bits are needed for the fractional part of the Optimal Filtering amplitude and phase weights, respectively. The total number of bits needed for the fixed-point representation of the OF weights is obtained with the fractional bits and the bits required to represent the integer part of the weights which is called the range. The range of the amplitude OF weights is between  $\pm 1$  ADC count, then 2 signed bits are enough for the integer part of the amplitude, and the range of the phase OF weights is between  $\pm 30 \text{ ns} \times \text{ADC count}$ , thus 6 signed bits are enough for the phase range (Figure 3.7 shows the values of the OF weights for different initial phases). Therefore, for amplitude and phase weights, 16-bit signed words are the appropriate choice for their fixed-point representation.



**Figure 3.20:** (a) Uncertainty on the amplitude versus the number of fractional bits of the amplitude Optimal Filtering weights, for low gain and physics events with amplitude equal to 1200 ADC count and an initial phase of 0 ns. (b) Uncertainty on the phase versus the number of fractional bits of the phase OF2 weights, for low gain and physics events with amplitude equal to 0, 500 and 1200 ADC count and initial phase equal to 0 ns.

The OF weights calculated offline are converted to fixed-point numbers and packed in 32-bit words with the convenient format before being sent to the ROD DSPs. The software responsible for that is organized in an online CMT package called TileDSPofc and is part of the ATLAS Tile Online CVS repository. The source code can be found in [43].

In order to convert the offline OF weights to fixed-point numbers we need to find the correct scale for the weights (different for amplitude and phase weights). Since the DSPs can implement fast shift instructions the scale is chosen to be  $2^m$ , where  $m$  is obtained by requiring:

$$2^{16} - 1 = 2^m \max\{w_i, \sum_{i=1}^n w_i\} \quad , \quad (3.45)$$

then,

$$m = \text{trunc} \left( \frac{\log \left( \frac{2^{16}-1}{\max\{w_i, \sum_{i=1}^n w_i\}} \right)}{\log 2} \right) \quad , \quad (3.46)$$

where  $\max$  takes the maximum between each weight ( $w_i$ ) and the sum of all the weights ( $\sum_{i=1}^n w_i$ ), and  $\text{trunc}$  takes the nearest integer not larger in absolute value. In order to get the OF weights in 16-bit fixed-point representations, each weight and the total sum are multiplied by the factor ( $2^m$ ) and rounded to the nearest integer.

### 3.3.2 Online Energy Calibration

A linear calibration is applied to the reconstructed amplitude in order to feed the ATLAS 2nd level trigger with the energy calibrated in MeV. The calibration factors are an offset ( $n$ ) and a slope ( $m$ ), which are applied to the reconstructed amplitude ( $A[ADC]$ ) in the way:

$$A[\text{MeV}] = m (n + A[ADC]) \quad , \quad (3.47)$$



where the offset  $n$  is in ADC counts and the slope  $m$  carries the energy units factor that multiply the amplitude  $A$  and the offset, which are calculated in ADC counts. These calibration constants,  $m$  and  $n$ , are also packed in signed 16-bit words, following the same procedure as the Optimal Filtering weights described in Section 3.3.1, for a posterior uploading to the ROD DSPs. There are four types of calibration factors available at the DSP level:

- *OnlineADC*: amplitude in ADC counts (type 0),
- *OnlinePicoCoulomb*: amplitude in pC (type 1),
- *OnlineCesiumPicoCoulomb*: amplitude in Cesium equalized pC (type 2),
- *OnlineMegaElectronVolt*: amplitude in MeV (type 3).

The prefix *Online-* indicates that these calibration factors are applied online and the calibrated energies used for the second level trigger to make a decision. Afterward, a more complex calibration can be applied offline, for a more precise analysis, by uncalibrating the amplitude and applying new factors which are stored in the database with without prefix.

### 3.3.3 The Online Optimal Filtering algorithm

Once the Optimal Filtering weights for the amplitude and phase, the pulse shape values <sup>1</sup> and the energy calibration constants are converted to 16-bit fixed-point numbers, they are packed in arrays of 32-bit words (called OFW fragments) which are uploaded to the DSP through its parallel host port interface HPI.

The format proposed for these arrays is described in Figure 3.21. For each initial phase an OFW fragment is built, for 9 samples events the first 18 32-bit words contain the OF weights, pulse shapes and calibration factors for low gain and the next 18 32-bit words the same information for high gain, thus each OFW fragment is composed by 36 32-bit words. This format is chosen to easily allow

<sup>1</sup>The pulse shape values are needed to calculate the quality factors of the reconstruction. The constraints on the number of bits, concerning precision and range, are very similar to the amplitude OF weights.

parallel multiplications of the OF weights and the samples. For an event with 9 samples, the OF weights, for amplitude and phase, are arranged in 5 32-bit words. The 16 MSB of each word contain the OF weight  $i$  and the 16 LSB of the same word contain the OF weight  $i + 1$ , where  $i$  runs from 1 to 9. The samples are arranged in a similar way inside the DSP in order to implement the instructions shown in Figure 3.22. The place for the OF weight and the sample number 10 is filled with the negative sum of the OF weights and the pedestal estimation, respectively. In the case of the OF2 algorithm the sum of the weights is equal to zero and this operation has no effect, but in the case of the OF1 algorithm this operation allows to subtract the pedestal to all the samples:

$$A^{\text{OF1}} = \sum_{i=1}^n a_i (S_i - p) = \sum_{i=1}^n a_i S_i - p \sum_{i=1}^n a_i \quad , \quad (3.48)$$

$$A\tau^{\text{OF1}} = \sum_{i=1}^n b_i (S_i - p) = \sum_{i=1}^n b_i S_i - p \sum_{i=1}^n b_i \quad , \quad (3.49)$$

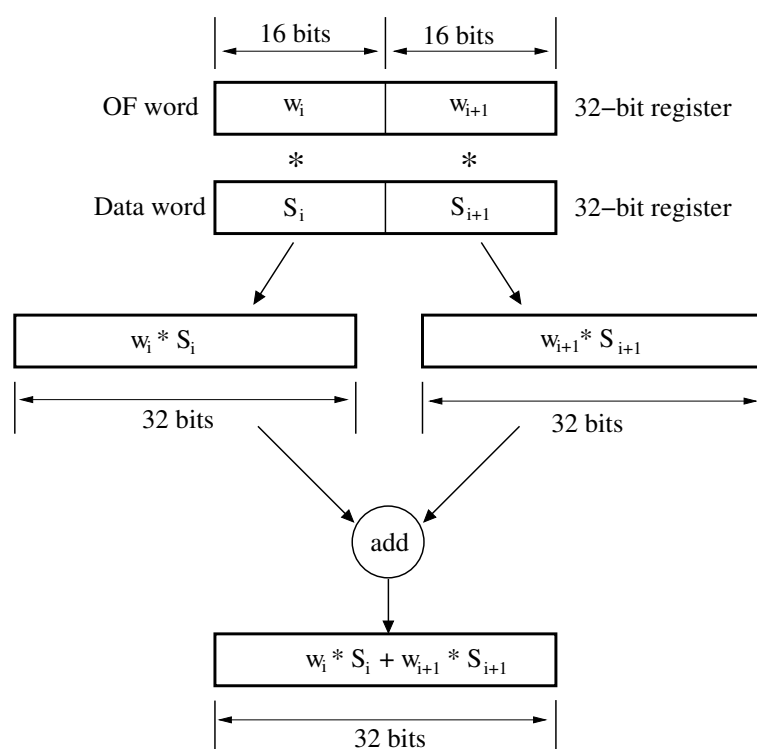
where  $p$  is the estimation of the pedestal. Each OFW fragment also includes the pulse shapes and energy calibration constants (offset and slope), as well as, all the scale factors applied to each value used for converting the floating-point numbers to fixed-point numbers, see again Figure 3.21.

In order to use the iteration mechanism we need to upload OFW fragments for different phases. In total, if we use phases between -100 and 100 ns in steps of 1 ns we need to upload 201 OFW fragments, starting from the initial phase of -100 ns and uploading sequentially the total amount of phases which makes a total of 28.5 kB of memory. At the end of the whole fragment (after the 201 phases) an additional 32-bit word with information about the OF weights and the calibration constants is added. The 8 LSB of this word contains 2 bits for the energy calibration type, 2 bits for the type of the pulse shape used to calculate the OF weights, 1 bit to flag the number of samples and 1 bit for the algorithm flavor (OF1 or OF2). Figure 3.23 shows the description of this word.

Currently, the weights used in the DSPs are calculated with a standalone software and later on written into POOL files which are stored in the ATLAS data

| Nb.<br>words | 32-bit words  |                     |                  |
|--------------|---------------|---------------------|------------------|
|              | 16 bits       | 16 bits             |                  |
| 0            | $a_1$         | $a_2$               | L<br>O<br>W      |
| 1            | $a_3$         | $a_4$               |                  |
| 2            | $a_5$         | $a_6$               |                  |
| 3            | $a_7$         | $a_8$               |                  |
| 4            | $a_9$         | $-\sum_{i=1}^n a_i$ |                  |
| 5            | $b_1$         | $b_2$               | G<br>A<br>I<br>N |
| 6            | $b_3$         | $b_4$               |                  |
| 7            | $b_5$         | $b_6$               |                  |
| 8            | $b_7$         | $b_8$               |                  |
| 9            | $b_9$         | $-\sum_{i=1}^n b_i$ |                  |
| 10           | Scale $b$     | Scale $a$           |                  |
| 11           | $g_1$         | $g_2$               |                  |
| 12           | $g_3$         | $g_4$               |                  |
| 13           | $g_5$         | $g_6$               |                  |
| 14           | $g_7$         | $g_8$               |                  |
| 15           | $g_9$         | Scale $g$           |                  |
| 16           | Scale offset  | Scale slope         |                  |
| 17           | Calib. Offset | Calib. Slope        |                  |
| 18           | $a_1$         | $a_2$               | H<br>I<br>G<br>H |
| 19           | $a_3$         | $a_4$               |                  |
| ...          | ...           | ...                 |                  |
| ...          | ...           | ...                 |                  |
| 34           | Scale offset  | Scale slope         |                  |
| 35           | Calib. Offset | Calib. Slope        |                  |

**Figure 3.21:** Description of the OFW fragment, the first 18 words corresponds to the OF weights for low gain and the next 18 words corresponds to OF weights for high gain.



**Figure 3.22:** Scheme of the multiplication of the OF weights by two consecutive samples inside the ROD DSPs.

|                                                                         |           |    |    |   |   |    |  |   |
|-------------------------------------------------------------------------|-----------|----|----|---|---|----|--|---|
| 31                                                                      | 16        | 15 | 8  | 7 |   |    |  | 0 |
| XXXX XXXX XXXX XXXX                                                     | XXXX XXXX | CC | RR | S | A | XX |  |   |
| C: Calibration online units                                             |           |    |    |   |   |    |  |   |
| 0 - <i>OnlineADC</i>                                                    |           |    |    |   |   |    |  |   |
| 1 - <i>OnlinePicoCoulomb</i>                                            |           |    |    |   |   |    |  |   |
| 2 - <i>OnlineCesiumPicoCoulomb</i>                                      |           |    |    |   |   |    |  |   |
| 3 - <i>OnlineMegaElectronVolt</i>                                       |           |    |    |   |   |    |  |   |
| R: Type of pulse shape used to calculated the Optimal Filtering weights |           |    |    |   |   |    |  |   |
| 0 - Physics                                                             |           |    |    |   |   |    |  |   |
| 1 - Laser or LED                                                        |           |    |    |   |   |    |  |   |
| 2 - Charge injection                                                    |           |    |    |   |   |    |  |   |
| S: Optimal Filtering weights for 7 or 9 samples                         |           |    |    |   |   |    |  |   |
| 0 - 7 samples                                                           |           |    |    |   |   |    |  |   |
| 1 - 9 samples                                                           |           |    |    |   |   |    |  |   |
| A: Algorithm type                                                       |           |    |    |   |   |    |  |   |
| 0 - OF1, Optimal Filtering 2 parameters, energy and phase               |           |    |    |   |   |    |  |   |
| 1 - OF2, Optimal Filtering 3 parameters, energy, phase and pedestal     |           |    |    |   |   |    |  |   |
| X: Not used                                                             |           |    |    |   |   |    |  |   |

**Figure 3.23:** Description of the last word uploaded to the DSP after the 201 OFW fragments, this word contains information about the Optimal Filtering weights and energy calibration factors.

acquisition machines and added into a conditions database with an interval time of validity. The OF weights are read from these POOL files using an online CMT package called TileUseDB. This package is the link between the online environment and the ATLAS offline software. Before starting a run, the OF weights are converted on the fly to OFW fragments, the energy calibration constants are added to each OFW fragment and after the 201 phases the final word with OF information is also added before being sent to the DSPs.

The DSP memory is accessible from a host processor through the parallel host port interface (HPI). The ROD DSPs are accessible from VME bus through a host processor which is the single board computer that handles the VME bus of a ROD crate. The TileVmeROD library [35] implements the methods to upload the OF weights to the DSPs using this parallel HPI.

The TileCal ROD system receives data from the TileCal front-end electronics when a LVL1 trigger signal is asserted. During commissioning, signals produced by cosmic muons are read-out with 9 digitized samples and their corresponding gain

which can be either high or low gain. Each front-end board sends 16 DMU blocks of data and each block contains information from 3 photomultipliers. Consequently the DSP receives from each drawer 16 data blocks and each block contains 9 samples of three read-out channels. For a more detailed description of the ROD input data format see Section 2.1.4 and Figure 2.5, 2.6 and 2.7.

The DSP reconstruction algorithm extracts from the input data stream the information of the 9 samples and their gain for each channel. The samples from a DMU are packed in 9 32-bit words and each word contains the 10-bit sample taken at  $t_i$ , of the three channels from the corresponding DMU. The DSP extracts the samples for a given channel and repacks them in 32-bit words, where the 16 MSB contain the sample  $i$  and the 16 LSB contain the next sample,  $i + 1$  of a specific read-out channel. An additional sample is added, this sample number 10 is filled with the pedestal estimation, which is the first sample ( $S_1$ ), if the maximum is found between the central and the last sample inclusive, or the last sample ( $S_9$ ), if the maximum is found before the central sample. We are aware that the estimation of the pedestal as the last sample is not the appropriated choice due to an undershoot of the pulse shape at this position, however, during commissioning the timing of the signal is extremely variable and in many cases the first sample contains a large signal contribution, being the last sample a better choice than the first sample.

The online reconstruction follows the flow chart of the iterative procedure described in Figure 3.12, the DSP algorithm calculates the maximum and the minimum of the samples and their position within the samples. The criteria to identify signal or pedestal events is the same as in the offline criteria, however, the limits of  $3\sigma_{\text{noise}}$  and  $12\sigma_{\text{noise}}$  are approximated inside the DSP to integer values, see Table 3.2. The number of iterations is defined in the DSP code. During commissioning, it is set to 3 iterations, which means that the amplitude is calculated three times.

During the amplitude and phase reconstruction the samples are multiplied by the OF weights using the function shown in Figure 3.22. The sample that contains

**Table 3.2:** DSP thresholds selection depending on the gain for signal and pedestal identification.

| Gain | Threshold                 | DSP value<br>(ADC counts) |
|------|---------------------------|---------------------------|
| LOW  | $3\sigma_{\text{noise}}$  | 2                         |
| LOW  | $12\sigma_{\text{noise}}$ | 8                         |
| HIGH | $3\sigma_{\text{noise}}$  | 5                         |
| HIGH | $12\sigma_{\text{noise}}$ | 20                        |

the pedestal estimation (sample number 10) is multiplied by the negative sum of Optimal Filtering weights, which in the case of OF2 is zero and in the case of OF1 is different from zero. This way both algorithms (OF1 and OF2) can be applied using the same reconstruction routine by changing the OF weights at the beginning of a run.

The same mechanism is applied to calculate the amplitude and the phase. But in order to calculate the phase, the linear combination of the samples is divided by the calculated amplitude. However, the DSP cannot implement divisions, thus this operation is implemented through a look-up table of 16-bit unsigned words. The look-up table contains values for amplitudes between 1 and 1200 ADC counts in steps of 0.5 ADC counts.

When the reconstruction is finished, the amplitude is online calibrated to energy units, which can be either ADC counts, pC, Cesium equalized pC or MeV. The phase is calculated in ns and the quality factor in ADC counts. The reconstructed parameters of a given channel are packed together in a 32-bit word and sent to the 2nd level trigger with the format described in next Section 3.3.4.

### 3.3.4 Output data format description

The ROD fragments follow the ATLAS data format requirements described in [44]. Each subfragment should be composed by a 32-bit subfragment header,

which is set to 0xff1234ff, a 32-bit fragment size word and a 32-bit fragment identifier word additionally to the 32-bit data words. The fragment word contains the number of words inside the subfragment including the subfragment header, the fragment identifier and itself.

The fragment identifier word contains the drawer identifier in the 16 LSB. Table 3.3 shows the different drawer identifiers for the 64 modules of the four tile calorimeter barrels. The 16 MSB of the fragment identifier word are assigned to the fragment type which consists of the Optimal Filtering information (in the 8 upper bits) and the format identifier or fragment type (in the 8 lower bits). The 8 bits for the Optimal Filtering information contain the online calibration units identifier, 0 for ADC, 1 for pC, 2 for Cesium equalized pC and 3 for MeV. They also contain features of the OF weights such as 2 bits to flag which pulse shape is used (0 for physics, 1 for LED or laser and 2 for charge injection), 1 bit to flag if the weights are calculated for 7 or 9 samples, 1 bit for the algorithm flavor (0 for OF1 and 1 for OF2) and 2 bits for the number of iterations. The format identifier for the fragment described here is 0x4. The whole structure of the fragment identifier words is shown in Figure 3.24 and the general structure of the reconstruction fragment is also shown in Figure 3.25.

**Table 3.3:** Tile calorimeter drawer identifiers.

| TileCal Barrel | Barrel Identifier | Drawer Identifier |
|----------------|-------------------|-------------------|
| LBA            | 0x51              | 0x100 - 0x13F     |
| LBC            | 0x52              | 0x200 - 0x23F     |
| EBA            | 0x53              | 0x300 - 0x33F     |
| EBC            | 0x54              | 0x400 - 0x43F     |

The Optimal Filtering reconstruction parameters, amplitude, phase and quality factor, and the gain are sent in a single 32-bit word per channel which makes a total of 48 data words per drawer. From the 32 bits of each data word 1 bit is for the gain, 15 bits are used for packing the energy, 12 bits for packing the phase and 4 bits for the quality factor (see Figure 3.26).



|    |    |   |   |    |      |      |    |    |      |      |      |      |   |
|----|----|---|---|----|------|------|----|----|------|------|------|------|---|
| 31 |    |   |   | 24 | 23   |      | 16 | 15 |      |      |      |      | 0 |
| CC | RR | S | A | II | FFFF | FFFF |    |    | DDDD | DDDD | DDDD | DDDD |   |

C: Calibration online units

- 0 - *OnlineADC*
- 1 - *OnlinePicoCoulomb*
- 2 - *OnlineCesiumPicoCoulomb*
- 3 - *OnlineMegaElectron Volt*

R: Type of pulse shape used to calculated the Optimal Filtering weights

- 0 - Physics
- 1 - Laser or LED
- 2 - Charge injection
- 3 - simulated data\*

S: Optimal Filtering weights for 7 or 9 samples

- 0 - 7 samples
- 1 - 9 samples

A: Algorithm type

- 0 - OF1, Optimal Filtering 2 parameters, energy and phase
- 1 - OF2, Optimal Filtering 3 parameters, energy, phase and pedestal

I: Number of iterations

- 0 - No iterations
- 1 - Iterations (1 calculation of the energy)
- 2 - Iterations (2 calculation of the energy)
- 3 - Iterations (3 calculation of the energy)

F: Format identifier set to 0x4

D: Drawer identifier

\* If R field is equal 3, simulated data is used,  
and fields A and I merge together in 3 bits to encode offline algorithm types:

- 0 - Default (unknown)
- 1 - OF1, Optimal Filtering 2 parameters
- 2 - OF2, Optimal Filtering 3 parameters
- 3 - Fit Method
- 4 - Many Amplitudes Method
- 5 - Flat Filtering

**Figure 3.24:** Description of the 32-bit fragment identifier word of the ROD Optimal Filtering reconstruction subfragment. The least significant bits are on the right.

|                                   |     |           |
|-----------------------------------|-----|-----------|
| 31                                |     | 0         |
| Fragment identifier: 0xFF1234FF   |     |           |
| Fragment size: $48+3 = 51$ (0x33) |     |           |
| OF info                           | 0x4 | Drawer ID |
| OF data word of channel 0         |     |           |
| OF data word of channel 1         |     |           |
| ...                               |     |           |
| ...                               |     |           |
| OF data word of channel 47        |     |           |

**Figure 3.25:** Description of the ROD Optimal Filtering reconstruction subfragment. The least significant bits are on the right.

|    |                          |      |      |      |      |                |      |      |
|----|--------------------------|------|------|------|------|----------------|------|------|
| 31 | 30                       |      | 16   | 15   |      | 4              | 3    | 0    |
| G  | EEE                      | EEEE | EEEE | EEEE | PPPP | PPPP           | PPPP | QQQQ |
| G: | High (1) or low (0) gain |      |      |      | E:   | Energy         |      |      |
| P: | Phase                    |      |      |      | Q:   | Quality Factor |      |      |

**Figure 3.26:** Description of the 32-bit data words of the ROD Optimal Filtering reconstruction subfragment type 0x4. The least significant bits are on the right.

### The gain

The signal generated in the tile calorimeter has two different amplification factors, high and low gain, with a 64 ratio between them. During physics runs only one gain is selected, the bit 31 of the OF data words is set to 1 if the high gain is selected and it is set to 0 if low gain is selected for a given channel.

### The energy

The energy of each channel is coded in 15-bits. The procedure to unpack the energy encoded in each OF data words is first to get the 15 bits from this word, then subtract an offset and finally divide it by a factor which depends on the energy units:

$$E = \frac{(\text{value} - \Delta E)}{2^m} \quad , \quad (3.50)$$

where value is the integer number from the 15 bits of the OF data word,  $\Delta E$  and  $m$  are shown for each type of energy units in Table 3.4 and 3.5 for low and high gain respectively. Table 3.4 and 3.5 also show the maximum and minimum energy thresholds encoded in this format and the precision of the energy for the different energy units which is smaller than the uncertainty on the energy due to the samples precision. If the reconstructed value is out of the range the energy is saturated to the maximum or the minimum value inside the ROD DSPs.

**Table 3.4:**  $\Delta E$ , number of fractional bits ( $m$ ), minimum and maximum energy thresholds and the precision of the energy for the different energy units and low gain.

| Energy Units                   | $\Delta E$ | $m$ | $E_{\min}$ | $E_{\max}$ | precision |
|--------------------------------|------------|-----|------------|------------|-----------|
| <i>OnlineADC</i>               | 512        | 4   | -32        | 2016       | 0.0625    |
| <i>OnlinePicoCoulomb</i>       | 512        | 5   | -16        | 1008       | 0.03125   |
| <i>OnlineCesiumPicoCoulomb</i> | 512        | 5   | -16        | 1008       | 0.03125   |
| <i>OnlineMegaElectron Volt</i> | 512        | -5  | -16384     | 1032160    | 32        |

**Table 3.5:**  $\Delta E$ , number of fractional bits ( $m$ ), minimum and maximum energy thresholds and the precision of the energy for the different energy units and high gain.

| Energy Units                   | $\Delta E$ | $m$ | $E_{\min}$ | $E_{\max}$ | precision     |
|--------------------------------|------------|-----|------------|------------|---------------|
| <i>OnlineADC</i>               | 2048       | 4   | -128       | 1920       | 0.0625        |
| <i>OnlinePicoCoulomb</i>       | 2048       | 11  | -1         | 15         | 0.00048828125 |
| <i>OnlineCesiumPicoCoulomb</i> | 2048       | 11  | -1         | 15         | 0.00048828125 |
| <i>OnlineMegaElectron Volt</i> | 2048       | 1   | -1024      | 15360      | 0.5           |

### The phase

A total of 12 bits are assigned to encode phase values from -128 ns up to 127 ns. Thus 8 bits are needed for the range and 4 are used for the precision (fractional bits). Consequently, at the 2nd level trigger the phase is obtained with a maximum precision of  $2^{-4}$  ns or 0.0625 ns, accounting only for the output data format. In order to extract the correct phase value in ns from the bytestream one should get the 12 bits from the OF data words, subtract an offset of 2048 and divide by  $2^4$ :

$$\tau = \frac{(\text{value} - \Delta\tau)}{2^n} \quad \text{with} \quad \Delta\tau = 2048 \quad \text{and} \quad n = 4 \quad , \quad (3.51)$$

where value is the integer value from the 12 bits of the OF data word. If the reconstructed phase is larger in absolute value than 128 ns the value is saturated to  $\pm 128$  ns inside the ROD DSPs.

### The quality factor

The quality factor is encoded in 4 bits; values from -1 up to 29 counts are sent, where -1 means that the event is tagged as pedestal and that it was reconstructed using non iterative procedure with Optimal Filtering weights for initial phase ( $\tau_0$ ) equal to 0 ns. In order to decode the quality factor, one should bet the 4 bits from the OF data words subtract an offset equal to 1 and multiply it by 2:

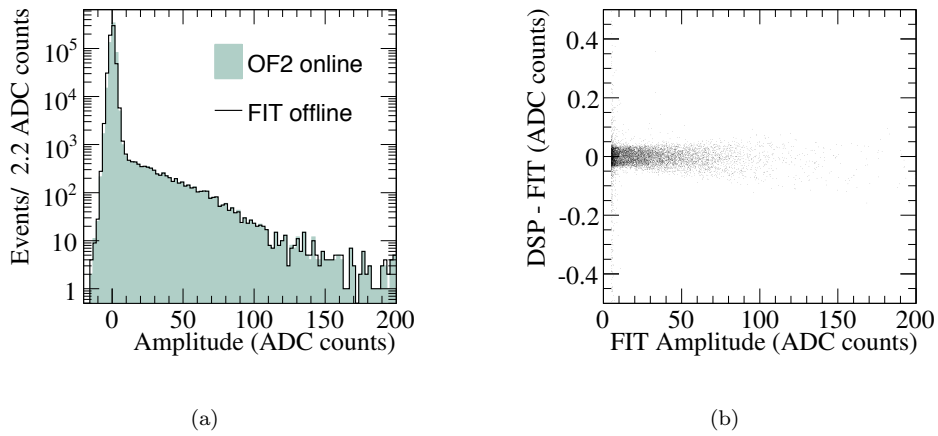
$$Q_F = (\text{value} - \Delta Q_F) \times 2 \quad \text{with} \quad \Delta Q_F = 1 \quad , \quad (3.52)$$

where value is the integer value from the 4 bits of the OF data word. If the reconstructed quality factor is larger than 29 the value is saturated inside the ROD DSPs.

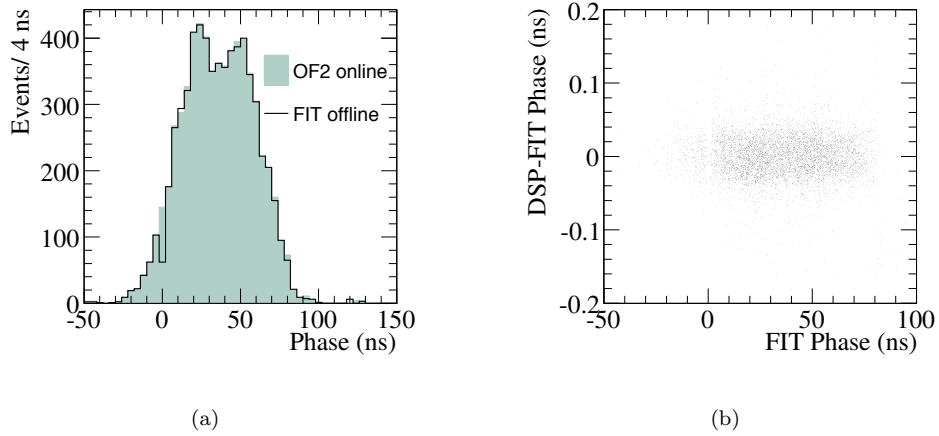
### 3.3.5 Comparison of the online and offline reconstruction

Since July 2006 several runs of cosmic rays were acquired and reconstructed online in the ROD DSPs. Figure 3.27(a) shows the histogram of the reconstructed amplitude in the ROD DSPs (online) and the offline reconstruction using FIT method, for all operative channels during the acquisition. The large tail corresponds to energy deposited by cosmic muons, while the peak around zero corresponds mostly to electronic noise. The agreement between both reconstructions is around 99 % for amplitudes above  $3\sigma$  of the noise, see Figure 3.27(b). For amplitudes smaller than  $3\sigma$  the difference between the online and offline reconstruction is expected to be larger due to the low signal to noise ratio.

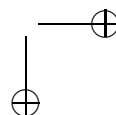
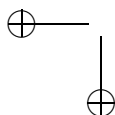
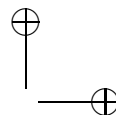
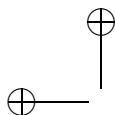
Figure 3.28(a) shows the online and offline phase reconstruction for amplitudes larger than  $3\sigma$ . The relative error of the phase reconstruction is larger than the relative error of the amplitude, the use of a look-up table in the DSP contributes to increase this error. The difference for amplitudes above  $3\sigma$  of the noise is around 0.25 ns, see Figure 3.28(b).



**Figure 3.27:** (a) Histogram of the amplitude reconstruction using on-line Optimal Filtering (OF2) in the ROD DSPs and offline FIT for a run of cosmic muons (run number 61426). (b) Scattered plot of the difference between the online reconstruction of the amplitude using Optimal Filtering (OF2) and the offline reconstruction using FIT versus the offline reconstructed amplitude (run number 61426).



**Figure 3.28:** (a) Histogram of the phase reconstruction using online Optimal Filtering (OF2) in the ROD DSPs and offline FIT for a run of cosmic muons (run number 61426). (b) Scattered plot of the difference between the online reconstruction of the phase using Optimal Filtering (OF2) and the offline reconstruction using FIT versus the offline reconstructed phase (run number 61426).





## Chapter 4

# The Standard Model and Beyond

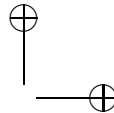
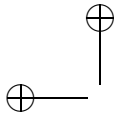
*“Prediction is very difficult, especially if it’s about the future”*

— Niels Bohr, 1885 – 1962

### 4.1 The Standard Model

The results of high energy physics experiments are up to now explained by the Standard Model (SM) [45–48]. This model describes the various interactions between elementary particles via the exchange of additional intermediate particles. There are two types of elementary particles, fermions and bosons. Matter is made out of fermions and intermediate particles are bosons.

Fermions are particles of spin  $\frac{1}{2}$  and can be classified in two types, quarks, that are sensitive to the strong interaction, and leptons, that are not, see Table 4.1. Electron (e), muon ( $\mu$ ) and tau leptons ( $\tau$ ) have integer electric charge,  $-1|e|$ .



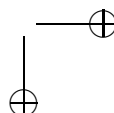
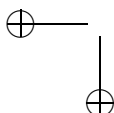
Each one has an associated neutral partner, the neutrino ( $\nu_e, \nu_\mu, \nu_\tau$ ). Quarks have fractional electric charge and an additional quantum number called colour. There are three different colours for each quark. In strong interactions, colour plays the role of the electric charge in electromagnetism. All particles have antiparticle partners. The three fermionic families have identical interactions, differing only in the mass. Three different fermionic families are presently known. There is no evidence of a 4th family containing light neutrinos [49–52]. Fermions from the 1st family are found in ordinary matter. Fermions from the 2nd and 3rd families are only found in cosmic experiments or created in accelerators.

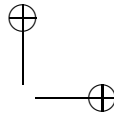
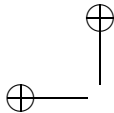
According to the Standard Model, the interactions between fermions are explained via the exchange of intermediate bosonic particles. Each boson is responsible for a different interaction. In this way, the photon is the mediator of the Electromagnetic force, in other words, two electrical charged fermions interact by exchanging a virtual photon. Table 4.2 shows the classification of the known forces and associated mediators. Although the graviton has not been detected experimentally, it has been included in the table for completeness.

The Standard Model is a gauge theory. This means that the Lagrangians of the electromagnetic, weak and strong interactions are invariant under local gauge transformations. The electromagnetic case is treated as an example of gauge invariance in section 4.1.1.

**Table 4.1:** Fundamental fermions.

|         | 1st family | 2nd family | 3rd family |
|---------|------------|------------|------------|
| leptons | e          | $\mu$      | $\tau$     |
|         | $\nu_e$    | $\nu_\mu$  | $\nu_\tau$ |
| quarks  | u          | c          | t          |
|         | d          | s          | b          |





**Table 4.2:** Fundamental forces and bosons.

| Force           | Theory          | Mediator   |
|-----------------|-----------------|------------|
| Strong          | Chromodynamics  | Gluon      |
| Electromagnetic | Electrodynamics | Photon     |
| Weak            | Flavordynamics  | W and Z    |
| Gravitational   | Gravitation     | (Graviton) |

#### 4.1.1 Quantum Electrodynamics (QED)

The Dirac Lagrangian for a free particle (using  $\hbar = c = 1$ ) is

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi. \quad (4.1)$$

It describes a free particle with spin  $\frac{1}{2}$ ,  $\psi$  being a four-component spinor called the *Dirac spinor*,

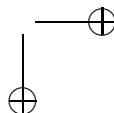
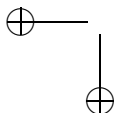
$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}. \quad (4.2)$$

This spinor contains a fermion with spin up and down and an anti-fermion with spin up and down (so 4 degrees of freedom in total). The Lagrangian is invariant under phase or global gauge transformations,

$$\psi \rightarrow e^{i\theta}\psi. \quad (4.3)$$

Now we consider a local phase, dependent on  $x^\mu$ , so the transformation is a local gauge transformation,

$$\psi \rightarrow e^{i\theta(x)}\psi. \quad (4.4)$$



We redefine a new phase  $\lambda(x) \equiv -\frac{1}{q}\theta(x)$  so the transformed Lagrangian is

$$\mathcal{L} \rightarrow \mathcal{L} + (q\bar{\psi}\gamma^\mu\psi) \partial_\mu\lambda. \quad (4.5)$$

In order to obtain a Lagrangian invariant under local gauge transformations and cancel the extra term, we need to add a new vector field transforming in the following way

$$A_\mu \rightarrow A_\mu + \partial_\mu\lambda, \quad (4.6)$$

and this is obtained by replacing the usual derivative by the so called *covariant derivative*:

$$D_\mu \equiv \partial_\mu + iq\lambda A_\mu. \quad (4.7)$$

The complete new Lagrangian is then

$$\mathcal{L} = [i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - (q\bar{\psi}\gamma^\mu\psi) A_\mu. \quad (4.8)$$

This Lagrangian is invariant under local gauge transformations, provided that the free Lagrangian of the vector field is invariant as well. This request implies that the vector field is massless. In general, the free Lagrangian of a vector field (Procca field) for a massless particle is

$$\mathcal{L} = \frac{-1}{16\pi} F^{\mu\nu} F_{\mu\nu} + \frac{1}{8\pi} \cancel{(m_A)^2} \overset{0}{A^\nu A_\nu}, \quad (4.9)$$

where the tensor field is defined as  $F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$ .

Therefore, starting from the Dirac Lagrangian and imposing local gauge invariance, we obtain the Lagrangian of Quantum Electrodynamics:

$$\mathcal{L} = [i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - \frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} - (q\bar{\psi}\gamma^\mu\psi) A_\mu, \quad (4.10)$$

describing the interaction of charged fermions of spin  $\frac{1}{2}$  with photons. The coupling constant of the interaction being  $g_e$ , proportional to the electric charge:

$$g_e = \sqrt{4\pi\alpha_e} = \sqrt{4\pi} q . \quad (4.11)$$

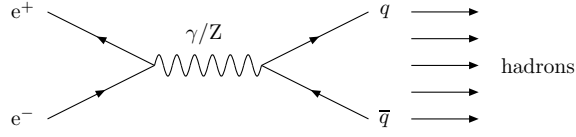
The global gauge transformation can be understood as a multiplication by a  $1 \times 1$  matrix  $U$ ,

$$\psi \rightarrow U\psi \quad \text{with} \quad UU^\dagger = 1 , \quad (4.12)$$

the group of such matrices is called  $U(1)$  and the corresponding symmetry is called “ $U(1)$  gauge symmetry”. Weak and strong interactions are generated in the same way, imposing  $U(2)$  and  $U(3)$  invariance, respectively. The problem of weak interactions is that the gauge intermediate bosons have non-zero masses, requiring a new mechanism in order to preserve local invariance. This mechanism is the so-called Higgs mechanism or spontaneous symmetry breaking as discussed in section 4.1.4.

### 4.1.2 Quantum Chromodynamics (QCD)

The rich spectroscopy of mesons and baryons [53] can be explained in terms of six different types of quarks with spin  $\frac{1}{2}$  (see Table 4.1). Since baryons are composite states of three quarks they have  $\frac{1}{2}$ -integer spin and obey Fermi statistics, implying a baryonic antisymmetric wave function. However, the  $\Delta^{++}$  baryon ( $J = \frac{3}{2}$ ) with  $J_3 = +\frac{3}{2}$  is described with a symmetric wave function, the only possibility for three up quarks with aligned spins ( $u^\uparrow u^\uparrow u^\uparrow$ ). In order to make the wave function antisymmetric, an additional quantum number is introduced. This quantum number is called colour, and should have three possible values, red, green and blue. The wave function of the  $\Delta^{++}$  baryon is now described by three up quarks with aligned spins and different colour ( $u_r^\uparrow u_g^\uparrow u_b^\uparrow$ ), allowing an antisymmetric wave-function.



**Figure 4.1:** Feynman diagram of  $e^+e^- \rightarrow \text{hadrons}$ , mediated by a photon ( $\gamma$ ) or a Z boson.

The number of colours is clearly measured using the ratio:

$$R_{e^+e^-} \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}. \quad (4.13)$$

At energies well below the Z mass, the dominant process is photon exchange (see Figure 4.1) and the approximate value of the ratio is:

$$R_{e^+e^-} \approx N_C \sum_{f=1}^{N_f} Q_f^2. \quad (4.14)$$

This ratio was found to be consistent with  $N_C$  equal to three [54–57]. Additional evidence for this result is obtained using the measurement of the  $\tau$  lepton decay [58] and also  $\pi^0 \rightarrow \gamma\gamma$  [53]. Therefore, each quark exists in three different states of colour (red, green and blue).

The Lagrangian that describes the interactions of three coloured quarks with equal mass is:

$$\mathcal{L} = \sum_i \bar{\psi}^i \gamma^\mu \partial_\mu \psi^i - m \bar{\psi}^i \psi^i, \quad \text{where } i = r, g, b. \quad (4.15)$$

The notation is simplified by using a new definition of the field  $\psi$ :

$$\psi \equiv \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}, \quad \bar{\psi} = (\bar{\psi}_r, \bar{\psi}_g, \bar{\psi}_b), \quad \mathcal{L} = i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi. \quad (4.16)$$

This Lagrangian is simply the Dirac Lagrangian,  $\psi$  being a three component object. Since the new Lagrangian contains three particles with the same mass, it exhibits a  $U(3)$  symmetry, in the same way that the QED Lagrangian exhibits a  $U(1)$  symmetry. So the Lagrangian is invariant under transformations:

$$\psi \rightarrow U\psi \quad \text{with} \quad U^\dagger U = 1, \quad (4.17)$$

where  $U$  is now a  $3 \times 3$  matrix of the form:  $U = e^{iH}$ ,  $H$  being an hermitian  $3 \times 3$  matrix. This matrix can always be expressed in terms of eight real numbers  $\mathbf{a}$ ,  $(a_1, a_2, \dots, a_8)$ , and an angle  $\theta$ :

$$H = \theta I + \boldsymbol{\lambda} \cdot \mathbf{a}, \quad (4.18)$$

where  $I$  is the  $3 \times 3$  identity matrix and  $\boldsymbol{\lambda}$  are the eight Gell-Mann matrices (generators of the  $SU(3)$  algebra). Consequently, the symmetry group  $U(3)$  is equivalent to the group  $U(1) \times SU(3)$ :

$$U = e^{iH} = e^{i\theta} e^{i\boldsymbol{\lambda} \cdot \mathbf{a}}, \quad \det(e^{i\boldsymbol{\lambda} \cdot \mathbf{a}}) = 1. \quad (4.19)$$

The  $U(1)$  symmetry is related to baryon number conservation and is not a local gauge symmetry. In the following we consider a Lagrangian invariant under local  $SU(3)$  gauge transformations:

$$\psi \rightarrow S\psi, \quad \text{where} \quad S \equiv e^{-iq\boldsymbol{\lambda} \cdot \boldsymbol{\phi}(\mathbf{x})}, \quad \text{and} \quad \boldsymbol{\phi}(\mathbf{x}) \equiv -\frac{1}{q}\mathbf{a}(\mathbf{x}). \quad (4.20)$$

The strong charge (colour charge) for Chromodynamics is denoted by the symbol  $q$ . The same procedure as in Electrodynamics, i.e. replacing the usual derivative by the *covariant derivative*:

$$D_\mu \equiv \partial_\mu + iq\boldsymbol{\lambda} \cdot \mathbf{A}_\mu, \quad (4.21)$$

yields 8 massless new gauge fields. The approximate transformation rule for  $\mathbf{A}$  is

$$\mathbf{A}'_\mu \cong \mathbf{A}_\mu + \partial_\mu \boldsymbol{\phi} + 2q(\boldsymbol{\phi} \times \mathbf{A}_\mu), \quad (4.22)$$

assuming small values of  $\phi$ . The resulting Lagrangian is:

$$\mathcal{L} = [\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - (q\bar{\psi}\gamma^\mu\lambda\psi) \mathbf{A}_\mu. \quad (4.23)$$

The eight gauge fields are identified with the eight colours of the gluon. Then the final Lagrangian for Chromodynamics is obtained by adding the free Lagrangian for gluons:

$$\mathcal{L} = [\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi] - \frac{1}{16\pi} \mathbf{F}^{\mu\nu} \cdot \mathbf{F}_{\mu\nu} - (q\bar{\psi}\gamma^\mu\lambda\psi) \mathbf{A}_\mu, \quad (4.24)$$

with  $\mathbf{F}^{\mu\nu} \equiv \partial^\mu \mathbf{A}^\nu - \partial^\nu \mathbf{A}^\mu - 2q(\mathbf{A}^\mu \times \mathbf{A}^\nu)$ .

The strong charge  $q$  appearing in the Lagrangian is related to the strong coupling constant,  $g_s$ , defined as:

$$g_s = \sqrt{4\pi} 2q = \sqrt{4\pi\alpha_s}. \quad (4.25)$$

A new feature of the strong coupling constant is that  $g_s$  depends on the distance between quarks. At short distances (high energies), the strong coupling constant becomes small. This property is called *Asymptotic freedom*. Therefore, quarks inside hadrons behave almost as free particles in high energy interactions, allowing perturbative calculations (Feynman rules). On the contrary, at low energies,  $g_s$  becomes larger. At distances larger than  $10^{-15}$  m, the strong force becomes so intense that new quark-antiquark pairs are created. As a result, quarks only appear in colourless states inside baryons and mesons. This property is called *Confinement*.

### 4.1.3 Electroweak Interactions

Similarly to Quantum Electrodynamics and Chromodynamics, the Electroweak (EW) Lagrangian is built imposing the symmetry group  $SU(2)_L \times U(1)_Y$ . The free



Lagrangian is:

$$\mathcal{L} = \sum_{j=1}^3 i\bar{\psi}_j \gamma^\mu \partial_\mu \psi_j, \quad (4.26)$$

supposing for the moment that fermions are massless. Imposing local gauge invariance under the  $SU(2)_L \times U(1)_Y$  group we arrive to the EW Lagrangian with 4 massless bosons,

$$\mathcal{L} = \sum_{j=1}^3 i\bar{\psi}_j \gamma^\mu D_\mu \psi_j - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu}, \quad (4.27)$$

where

$$\begin{aligned} D_\mu \psi_j &\equiv \left( \partial_\mu - ig \frac{\boldsymbol{\tau}}{2} \cdot \mathbf{W}_\mu - ig' \frac{y_j}{2} B_\mu \right) \psi_j, \\ B_{\mu\nu} &\equiv D_\mu B_\nu - D_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} \equiv D_\mu \mathbf{W}_\nu - D_\nu \mathbf{W}_\mu + g \mathbf{W}_\mu \times \mathbf{W}_\nu. \end{aligned} \quad (4.28)$$

Being  $\boldsymbol{\tau}$  the Pauli matrices,  $y_j$  the weak hypercharge and  $g$  and  $g'$  the interaction couplings.

The three bosons,  $\mathbf{W} = (W^1, W^2, W^3)$ , are associated with the gauge group  $SU(2)_L$  and another boson  $B$  is associated with the gauge group  $U(1)_Y$ . These gauge bosons are associated with  $W^\pm$ ,  $Z$  and  $\gamma$  in the following way:

$$W_\mu^\pm \equiv \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2), \quad (4.29)$$

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}. \quad (4.30)$$

where the angle  $\theta_W$  is called Weinberg angle. The coupling constant,  $g$  and  $g'$ , are related with the QED coupling constant,  $g_e$ , by:

$$g \sin \theta_W = g' \cos \theta_W = g_e. \quad (4.31)$$

This model explains in an accurate way the electroweak interaction, but is incomplete since it only allows massless fermions and bosons. The photon is certainly massless but the other three bosons,  $W^\pm$  and  $Z$ , discovered in 1983 at the CERN SPS collider [59, 60] have non-zero masses. The addition of mass terms violates local gauge invariance and spoils the renormalizability of the theory. Therefore, it is necessary to introduce a new mechanism to give mass to bosons and fermions. This mechanism is called the Higgs mechanism.

#### 4.1.4 Spontaneous Symmetry Breaking

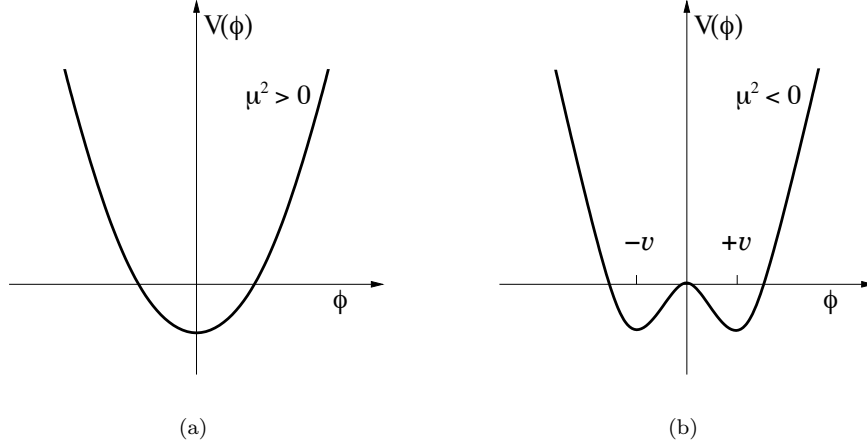
There is a way to generate massive particles without breaking gauge invariance in the Lagrangian. We consider in the following as a toy model the case of a scalar field with Lagrangian

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi) (\partial^\mu \phi) - \frac{1}{2} \mu^2 \phi^2 - \frac{1}{4} \lambda^2 \phi^4, \quad (4.32)$$

and  $\lambda^2 > 0$ . There are no odd terms in  $\phi$  so the Lagrangian is invariant under  $\phi \rightarrow -\phi$  transformations and no terms beyond  $\phi^4$  in order to have a renormalizable theory.

Depending on the sign of  $\mu^2$ , the potential can have a single minimum or various minima as shown in Figure 4.2(a) and Figure 4.2(b). If  $\mu^2 > 0$  the Lagrangian describes a field with mass  $\mu$  and four-particle self-interaction with coupling  $\lambda$ . The ground state (or vacuum state) corresponds to  $\phi = 0$ . If  $\mu^2 < 0$  the mass term has apparently an incorrect sign. However, a perturbation expansion should be performed in this case around a true vacuum, i.e. around a state with minimum energy. For  $\mu^2 < 0$  the minimum energy state is  $\phi = \pm v$  where  $v = \sqrt{-\mu^2/\lambda^2}$ . Perturbative calculations should involve expansions around this minimum, therefore the Lagrangian has to be rewritten in terms of a new field  $\eta = \phi \pm v$ . Selecting the solution  $\eta = \phi - v$ , we obtain

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \eta)^2 - \lambda^2 v^2 \eta^2 - \lambda^2 v \eta^3 - \frac{1}{4} \lambda^2 \eta^4 + \text{const.} \quad (4.33)$$



**Figure 4.2:** Graph of the potential of the field  $\phi$ ,  $V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda^2\phi^4$ , as function of  $\phi$ . For  $\mu^2 > 0$ , (a), with vacuum state at  $\phi = 0$  and for  $\mu^2 < 0$ , (b), for two vacuum states  $\phi = \pm v = \pm \sqrt{-\mu^2/\lambda^2}$ .

This Lagrangian is equivalent to the Lagrangian in Eq. 4.32 but now the mass of the physical field  $\eta$  is positive:

$$m_\eta = \sqrt{2\lambda^2 v^2} = \sqrt{-2\mu^2}. \quad (4.34)$$

In order to generate a mass for the new field, the reflexion symmetry of the new Lagrangian is broken, i.e. the Lagrangian does not preserve the  $\eta \rightarrow -\eta$  symmetry. In general, the mechanism of breaking symmetries using the vacuum, instead of the Lagrangian, is called Spontaneous Symmetry Breaking. This mechanism, applied to local gauge fields, is able to generate masses for initially massless fermions and bosons.

We consider now the U(1) of a complex scalar field. The Lagrangian is:

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^* (\partial^\mu \phi) + \frac{1}{2} \mu^2 (\phi^* \phi) - \frac{1}{4} \lambda^2 (\phi^* \phi)^2, \quad (4.35)$$

where

$$\phi \equiv \phi_1 + i\phi_2, \quad \phi^* \phi = \phi_1^2 + \phi_2^2. \quad (4.36)$$

In order to have a Lagrangian invariant under local U(1) gauge transformations, the interaction with a vector field is introduced:

$$\begin{aligned} \mathcal{L} = & \frac{1}{2} [(\partial_\mu - iqA_\mu) \phi^*] [(\partial^\mu + iqA^\mu) \phi] \\ & + \frac{1}{2} \mu^2 (\phi^* \phi) - \frac{1}{4} \lambda^2 (\phi^* \phi)^2 - \frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu}, \end{aligned} \quad (4.37)$$

then we redefine new fields describing perturbations around the vacuum,

$$\eta \equiv \phi_1 - \mu/\lambda, \quad \xi \equiv \phi_2, \quad (4.38)$$

and the Lagrangian becomes

$$\begin{aligned} \mathcal{L} = & \left[ \frac{1}{2} (\partial_\mu \eta) (\partial^\mu \eta) - \mu^2 \eta^2 \right] + \left[ \frac{1}{2} (\partial_\mu \xi) (\partial^\mu \xi) \right] + \left[ -\frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} (q\frac{\mu}{\lambda})^2 A_\mu A^\mu \right] \\ & - 2i \left( q\frac{\mu}{\lambda} \right) (\partial_\mu \xi) A^\mu + q [\eta (\partial_\mu \xi) - \xi (\partial_\mu \eta)] A^\mu + \frac{\mu}{\lambda} (q)^2 \eta (A_\mu A^\mu) \\ & + \frac{1}{2} (q)^2 (\xi^2 + \eta^2) (A_\mu A^\mu) - \lambda \mu (\eta^3 + \eta \xi^2) - \frac{1}{4} \lambda^2 (\eta^4 + 2\eta^2 \xi^2 + \xi^4) + \text{const}. \end{aligned} \quad (4.39)$$

This Lagrangian describes a scalar field  $\eta$  with mass and a second scalar field without mass  $\xi$ , called a Goldstone boson. Moreover, this Lagrangian includes a mass term for the vector field  $A_\mu$ , so the vector  $A_\mu$  has also acquired mass. The rest of the terms represent couplings between the scalar particles and the field  $A_\mu$ .

Although this mechanism is able to give mass to a boson field, it is not satisfactory because a scalar massless field has appeared, the Goldstone boson, and no scalar massless particle exist in nature. In order to get rid of the Goldstone boson we can transform the original field using gauge invariance:

$$\phi \rightarrow \phi' = \phi'_1 + i\phi'_2 = (\cos \theta + i \sin \theta) (\phi_1 + i\phi_2). \quad (4.40)$$

If  $\theta = -\tan^{-1}(\phi_1/\phi_2)$ ,  $\phi'$  is real, and  $\xi \equiv \phi'_2 = 0$  so the Goldstone boson disappears from the Lagrangian:

$$\begin{aligned} \mathcal{L} = & \left[ \frac{1}{2} (\partial_\mu \eta) (\partial^\mu \eta) - \mu^2 \eta^2 \right] + \left[ -\frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} \left( q \frac{\mu}{\lambda} \right)^2 A_\mu A^\mu \right] \\ & + \frac{\mu}{\lambda} q^2 \eta (A_\mu A^\mu) + \frac{1}{2} q^2 \eta^2 (A_\mu A^\mu) - \lambda \mu \eta^3 - \frac{1}{4} \lambda^2 \eta^4 + \text{const.} \end{aligned} \quad (4.41)$$

This new Lagrangian describes a massive scalar field,  $\eta$ , the so-called Higgs boson, and a massive gauge field,  $A^\mu$ . In the Standard Model the Higgs mechanism [61] is used to give mass to the weak bosons  $Z$  and  $W^\pm$ , and to fermions as well. Unfortunately, the Higgs boson has not been discovered. A more detail study of the experimental mass limits for a SM neutral Higgs particle is presented in Section 4.1.5.

#### 4.1.5 The Higgs Boson

As discussed before, the introduction of a new scalar field in the Standard Model, the Higgs boson, allows mass terms for fermions and bosons. Unfortunately, the SM Higgs boson,  $H^0$ , has not been found and its mass depends on a free parameter of the theory, the coupling constant,  $\lambda$ . However, lower and upper mass limits can be obtained using theoretical arguments [62].

For a heavy Higgs, the coupling constant,  $\lambda$ , would rise with energy and, at a certain energy scale  $\Lambda$ , the coupling would become infinite. In order to prevent this, an upper limit on  $\lambda$  can be set, which is translated into an upper limit on the Higgs mass. If  $\lambda$  is very small, the contribution of the couplings between the Higgs field and the fermion fields can make the minimum of the scalar potential unstable below a scale  $\Lambda$ . The lower bound is chosen requiring the stability condition below the scale  $\Lambda$ . Selecting a scale  $\Lambda$ :

$$\Lambda = \Lambda_{\text{GUT}} \approx 10^{15} \text{ GeV}, \quad (4.42)$$

where the energy scale  $\Lambda_{\text{GUT}}$  is the Grand Unification scale, the mass of the Higgs boson should be in the mass range of about 130 to 190 GeV.

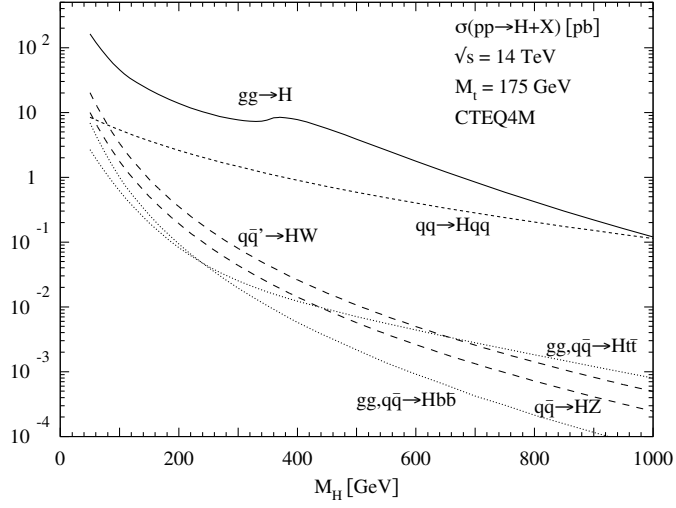
Direct searches of the SM Higgs boson mass, combining LEP data from the four experiments, ALEPH, DELPHI, L3 and OPAL, provide a 95 % CL lower bound of 114.4 GeV [63]. Indirect searches of the Higgs boson using high precision electroweak measurements sensitive to  $m_{H^0}$  via radiative corrections, set an upper limit on the mass of about 200 GeV at 95 % CL [64, 65].

The next hadron collider, the LHC (Large Hadron Collider), will be able to produce the Higgs boson over a large mass range. Figure 4.3(a) shows the Higgs production cross section as a function of Higgs mass. The most promising production channel is the gluon-gluon fusion,  $gg \rightarrow H$ , although the associated production,  $t\bar{t}H$ , through the W or Z fusion mechanism becomes important as well. Figure 4.3(b) shows the branching ratios for the various Higgs decay channels as a function of mass. The selection of an optimum decay channel for Higgs searches depends not only on the branching ratio but also on the signal-to-background ratio. Therefore, for a light Higgs,  $m_{H^0} < 130$  GeV, a convenient channel is  $H \rightarrow \gamma\gamma$  because of the very clear final state consisting in a couple of photons at high transverse momentum ( $p_T$ ). For the intermediate mass region,  $130 \text{ GeV} < m_{H^0} < 2m_Z$ , promising channels are  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  and  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ . For masses well above  $2m_Z$ , a gold-plated signature is  $H \rightarrow ZZ \rightarrow 4\ell$ , almost background free.

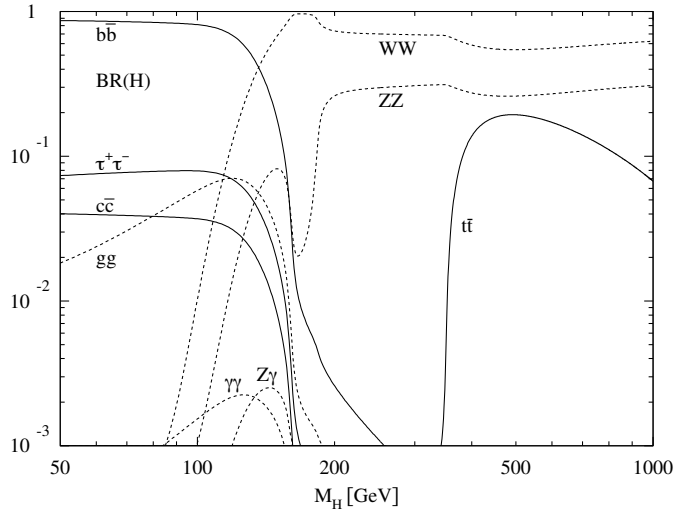
## 4.2 Beyond the Standard Model

The Standard Model explains most of the present data from high energy physics experiments. It describes the electromagnetic and weak interactions via the symmetry  $SU(2)_L \times U(1)_Y$  broken by the vacuum at the cost of introducing a new unobserved particle, the Higgs boson  $H^0$ . The strong force is described by the unbroken symmetry group  $SU(3)$  applied to colour. Due to gluon self-interactions, this theory is asymptotically free at high energies. At low energies the theory is expected to account for the confinement of quarks into colourless hadronic states.

Despite its great success, the Standard Model cannot be the ultimate theory for particle interactions. Many aspects are still unclear, for instance the Standard Model does not account for neutrino oscillations discovered recently [67–70].



(a)



(b)

**Figure 4.3:** SM Higgs production cross section in a hadron collider (a) and Higgs decay branching ratio (b) as a function of the Higgs mass [66].

Another important difficulty is the so-called hierarchy problem. Loop corrections to the scalar Higgs mass are quadratically divergent. If the cutoff  $\Lambda$  used to remove these divergences is of the order  $\Lambda_{\text{GUT}} \sim 10^{15}$  GeV, an incredible cancellation should occur between the bare mass and radiative corrections in order to obtain a Higgs mass below the TeV scale (this is also called the fine-tuning problem).

The perfect scenario would be the unification of all interactions. The Standard Model describes electroweak and strong interactions, but is unable to incorporate a consistent quantum theory of gravity. Moreover, the Standard Model contains a lot of arbitrary parameters, masses, couplings and mixing angles, to be obtained from experiments. Finally, the Standard Model does not provide an explanation for the matter-antimatter asymmetry in the universe, and for dark matter either.

Other models such as Supersymmetry, Little Higgs or Extra dimensions, try to explain all these problems, still reproducing the good achievements of the Standard Model.

### 4.2.1 Supersymmetry

As commented before, one of the main problems of the Standard Model are the quadratic divergences of the Higgs mass due to one-loop corrections (hierarchy problem). A solution to this problem is to cancel the fermion loops with the boson loops since they have opposite sign. This is possible by associating to each fermion a boson partner and vice-versa (Supersymmetry).

The hypothesis of Supersymmetry (SUSY) [71, 72] is therefore the existence of a new symmetry between fermions and bosons. For each fermion (boson) there is an associated boson (fermion), the supersymmetric partner. The supersymmetric partner has exactly the same mass and quantum numbers except the spin. Since no SUSY particles have been found experimentally, SUSY should be a broken symmetry. If the symmetry is broken, the quadratic loop contributions to the Higgs mass are still canceled, but the supersymmetric partners are much heavier than SM particles, and could appear at the TeV scale.



The conservation of baryon and lepton numbers can be imposed by introducing a new conserved quantum number, the  $R$ -parity:

$$R_P = (-1)^{(3B+L+2s)}, \quad (4.43)$$

where  $B$  is the baryon number,  $L$  the lepton number and  $s$  the spin. Standard model particles have  $R_P = +1$ , but the SUSY partners have  $R_P = -1$ . Conservation of this quantum number implies that SUSY particles should be created in pairs and that the lightest SUSY particle (LSP) is stable, hence a good candidate for dark matter.

The minimal supersymmetric extension of the Standard Model is MSSM. MSSM includes a broken supersymmetry that still provides the cancellation of quadratic divergences. It doubles the number of particles by adding supersymmetric partners to each SM particle. New interactions between SUSY and SM particles appear, and finally a second Higgs doublet is required in order to keep the Higgs mechanism at work. Table 4.3 shows a list of particles predicted by MSSM.

**Table 4.3:** Particle content of the MSSM.

| Bosons      |                                              | Fermions   |                                          |
|-------------|----------------------------------------------|------------|------------------------------------------|
| gluon       | $g^a$                                        | gluino     | $\tilde{g}^a$                            |
| weak bosons | $W^k (W^\pm, Z)$                             | wino, zino | $\tilde{W}^k (\tilde{W}^\pm, \tilde{Z})$ |
| photon      | $\gamma$                                     | photino    | $\tilde{\gamma}$                         |
| sleptons    | $\tilde{L}_i = (\tilde{\nu}, \tilde{e}^-)_L$ | leptons    | $L_i = (\nu, e^-)_L$                     |
|             | $\tilde{E}_i = \tilde{e}_R^+$                |            | $E_i = \tilde{e}_R^c$                    |
| squarks     | $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$     | quarks     | $Q_i = (u, d)_L$                         |
|             | $\tilde{U}_i = \tilde{u}_R^*$                |            | $U_i = u_R^c$                            |
|             | $\tilde{D}_i = \tilde{d}_R^*$                |            | $D_i = d_R^c$                            |
| higgses     | $H_1$                                        | higgsinos  | $\tilde{H}_1$                            |
|             | $H_2$                                        |            | $\tilde{H}_2$                            |

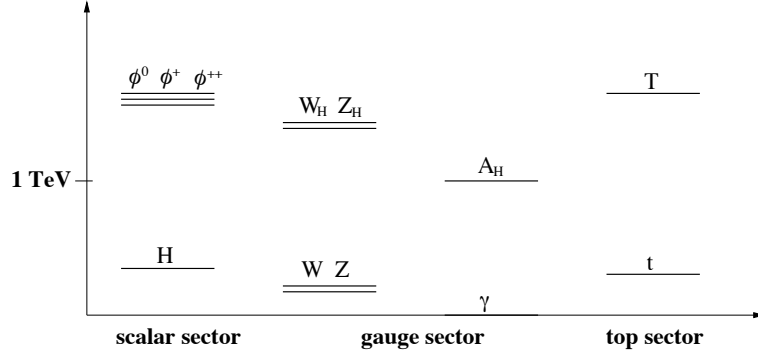
### 4.2.2 Little Higgs

The hierarchy problem of the Standard Model can be solved by Supersymmetry (see Section 4.2.1). This option has been explored extensively during the past years, but at present no SUSY partner has been found experimentally. Recently, new theories [73] and [74] have been proposed as an alternative to SUSY. These new theories are called Little Higgs (LH) because they succeed to keep the mass of the Higgs boson light, without introducing SUSY partners. In these theories, the Higgs boson is a pseudo-Goldstone boson, resulting from the breaking by the vacuum of a new global symmetry that includes the symmetry of the SM as a sub-group. This new global symmetry introduces new heavy particles in order to ensure the cancellation of radiative corrections to the Higgs mass at one loop order. The main difference with SUSY is that these new particles have the same spin as their SM partners. The Little Higgs models predict therefore new particles that should appear at the TeV scale.

There are many Little Higgs theories, depending on the new global group. The simplest model is the so-called Littlest Higgs [75]. It predicts the existence of a new heavy top-like quark with charge  $+\frac{2}{3}|e|$ ,  $T$ , that cancels the loop contribution of the top quark to the Higgs mass and new heavy gauge bosons,  $A_H$ ,  $W_H^\pm$  and  $Z_H$ , and a sector of heavy scalar particles  $\phi^0$ ,  $\phi^+$  and  $\phi^{++}$  that cancel the gauge boson loops of the SM and the corrections from the Higgs boson. Figure 4.4 shows the spectrum of the new particles predicted by the Littlest Higgs model.

### 4.2.3 Extra Dimensions

There are two fundamental energy scales, the electroweak scale,  $m_{EW} \sim 250$  GeV, and the Planck scale,  $M_{Pl} \sim 10^{19}$  GeV, where gravity becomes comparable to the electroweak and strong interactions. Electroweak and strong interactions have been tested around the  $\sim m_{EW}$  scale, however gravity has just been tested down to distances of  $\sim 1$ cm (compare with the Planck scale,  $M_{Pl} \sim 10^{-33}$  cm). Recent theories, based on the introduction of extra compactified dimensions, imply just one fundamental scale, the electroweak scale [76], solving in this way the hierarchy problem. Gravity appears as a very small force simply because it is confined



**Figure 4.4:** Particle content of the Littlest Higgs model, with corresponding masses.

mainly in the extra dimensions.

Assuming that there are  $n$  compactified extra dimensions of radius  $R$  and the Planck mass  $M_{\text{Pl}(4+n)}$ , in a  $4 + n$  space, is of the order of  $m_{\text{EW}}$ , the gravity potential for two masses ( $m_1$  and  $m_2$ ) separated a distance  $r$ , is described by a modified gravitational law:

$$V(r) = \frac{m_1 m_2}{M_{\text{Pl}(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \quad (r \ll R), \quad (4.44)$$

$$V(r) = \frac{m_1 m_2}{M_{\text{Pl}(4+n)}^{n+2} R^n} \frac{1}{r}, \quad (r \gg R). \quad (4.45)$$

The effective Planck mass,  $M_{\text{Pl}}$ , corresponding to  $r \gg R$ , is equal to

$$M_{\text{Pl}}^2 \sim M_{\text{Pl}(4+n)}^{n+2} R^n, \quad \text{with} \quad M_{\text{Pl}(4+n)} \sim m_{\text{EW}}, \quad (4.46)$$

which implies a value for the compactified radius of

$$R \sim 10^{\frac{30}{n}-17} \text{ cm} \times \left( \frac{1 \text{ TeV}}{m_{\text{EW}}} \right)^{1+\frac{2}{n}}. \quad (4.47)$$

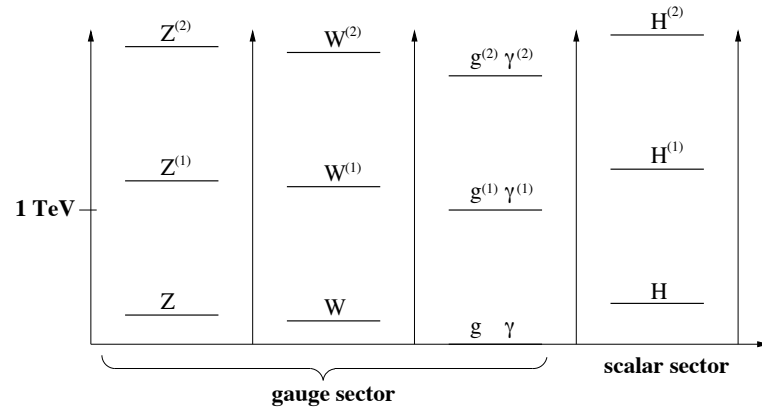
If the number of compactified dimensions is equal to 1 ( $n = 1$ ),  $R \sim 10^{13}$  cm, so deviations from the Newton law would be expected at solar distances, this being experimentally excluded. But for  $n \geq 2$ , the compactification radius is so small that deviations to the gravitation law would not be observable. In particular, for  $n = 2$ ,  $R \sim (10 \mu\text{m} - 1 \text{ mm})$ .

Any field that propagates in the extra compact dimensions has Kaluza-Klein (KK) excitations [77, 78], with mass of the order of the compactified scale. These new states are forbidden by high energy physics experiments up to masses of  $\sim 1 \text{ TeV}$ . For extra dimensions with compactification radius  $R \gg 1 \text{ TeV}^{-1}$  just gravity is allowed to propagate. This is an important feature of models with symmetric extra dimensions, i.e. with the same compactification radius. However, it is possible to build models with asymmetric extra dimensions. The *large* extra dimensions, with radius  $R_c \gg 1 \text{ TeV}^{-1}$ , are used to solve the hierarchy problem, and the *small* extra dimensions, with radius  $r_c \leq 1 \text{ TeV}^{-1}$ , allow matter and gauge field propagation.

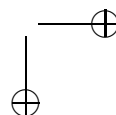
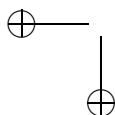
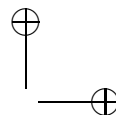
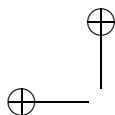
The simplest model is composed by at least 2 large extra dimensions where gravity propagates, and a small extra dimension where the gauge bosons and the Higgs propagates. The mass of the KK states are

$$M_n^2 = (nM_c)^2 + M_0^2, \quad (4.48)$$

where  $n$  is the KK state number,  $M_0$  is the mass of the zero mode, corresponding to a Standard Model gauge bosons,  $M_c$  is the compactification mass ( $\frac{1}{r_c}$ ) and  $M_n$  is the mass of the  $n$  excited mode. For one small extra dimension the couplings of KK resonances are equal to the Standard Model couplings except for a factor of  $\sqrt{2}$  [79]. Figure 4.5 shows the excited KK states and their masses for the boson sector in a model with one small compact extra dimension with compactification radius of 1 TeV.



**Figure 4.5:** Particle content with their mass, for a model with, at least, one compact extra dimension with compactification radius of  $\sim 1$  TeV.



## Chapter 5

# Searches beyond the Standard Model

*“Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed.”*

— Albert Einstein, 1879 – 1955

### 5.1 The LHC environment

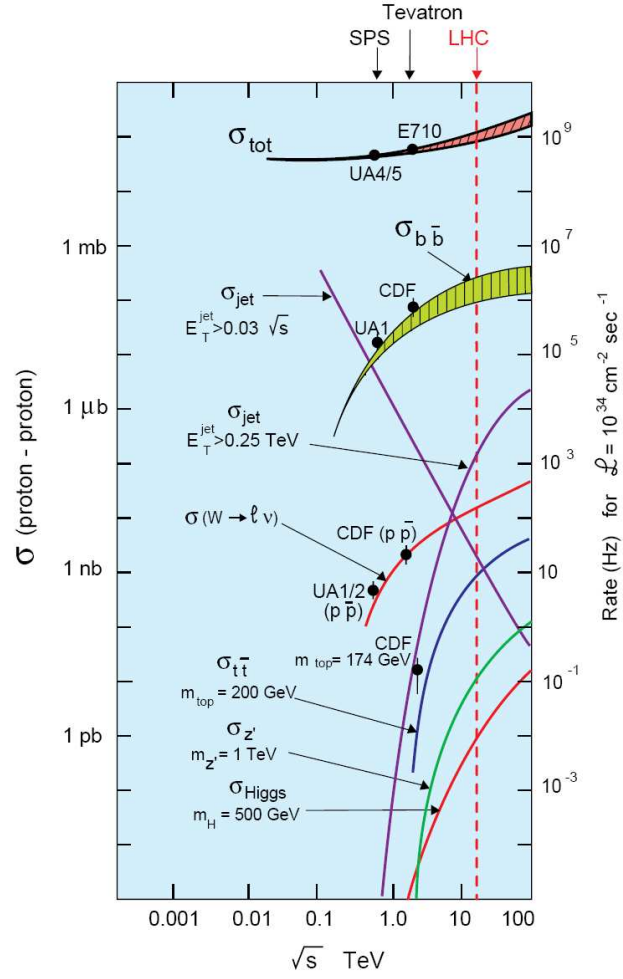
The LHC will provide proton-proton collisions at a challenging luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  and a center of mass energy of 14 TeV. Compared with previous experiments, a huge amount of events will be generated under these new conditions. In particular, the LHC will be a factory of all particles with masses up to the TeV with reasonable couplings with the Standard Model particles. However high luminosity and high energies entails some difficulties.

Figure 5.1 shows several production cross sections as a function of the center of mass energy. Events at high  $p_T$  are dominated by the strong QCD jet production, however more interesting channels have usually a smaller cross section since they may involve production of heavy particles or they may come from electroweak processes. For instance, we can see in the figure that the production cross section for jets with  $p_T > 250$  GeV is about 6 orders of magnitude larger than production of a SM Higgs boson with  $m_H = 500$  GeV. Consequently, at the LHC will be complicated to detect a particle relatively light (with mass in the few hundred GeV range) decaying into jets unless it is produced associated with other particles. However, for particles with masses in the TeV range the situation improves because the QCD  $\sigma_{\text{jet}}$  decreases fast with the invariant mass of the decay products.

Some models beyond the SM predict the existence of heavy particles (with mass around the TeV). The study of these resonances through their decay to heavy quarks is nowadays of special interest. Partly because the LHC will be able to confirm or rule out these models. In particular, searches of resonant structures in the invariant mass spectrum of  $t\bar{t}$  pairs has been recently published [80]. The analysis presented in [80] uses data from the  $p\bar{p}$  collider Tevatron at Fermilab with  $\sqrt{s} = 1.96$  TeV and recorded with the CDF II detector. The analysis sets an upper limit on the production cross section of a narrow heavy resonance  $Z'$  including the branching ratio decay to  $t\bar{t}$  ( $\sigma(p\bar{p} \rightarrow Z') \cdot \mathcal{BR}(Z' \rightarrow t\bar{t})$ ) of 0.64 pb at 95 % C.L for mass of the resonance above 700 GeV. However, it does not rule out a higher cross section for wide heavy resonances like the ones predicted in [79, 81, 82].

Because of its high luminosity the LHC will be a factory of all particles with mass up to few TeV. Searches of heavy resonances through their decay to heavy quarks and in particular to t-quarks will profit from the reduction of QCD jet background at high invariant mass and from the special signature that t-quarks produce since they decay to W and b-quark before hadronizing. That is the reason why top physics will be one of the most challenging in the LHC.





**Figure 5.1:** Production cross section at proton-proton colliders of Standard Model processes as a function of the machine center of mass energy  $\sqrt{s}$ .

## 5.2 Search for gluon excitations in ED models

### 5.2.1 Introduction

Kaluza-Klein (KK) excitations of gauge bosons are predicted in the context of some models with  $\text{TeV}^{-1}$  size extra-dimensions. Examples of such models are variants of the so-called ‘ADD model’ [83], with fermions confined to a D-brane, but with the difference that all gauge bosons may propagate in the bulk. The phenomenology of such models is discussed for example in [84]. The potential of ATLAS to observe KK excitations of the weak gauge bosons (Z and W) has already been discussed in [85] and [86]. KK gluon excitations are also expected as discussed in [79]. The KK excitations of Z and W are detected by reconstructing their leptonic decays. The detection of KK excitations of the gluon is much more challenging since only hadronic decays are expected. The sensitivity of LHC for such gluon excitations ( $g^*$  in the following) has already been discussed in [87]. In these searches, the presence of gluon excitations is detected by analyzing deviations in the dijet cross-section. An alternative is proposed in the present analysis, where the presence of  $g^*$  is detected by analyzing its decays into heavy quarks.

### 5.2.2 Cross-sections and Branching Ratios

According to [79], the couplings of  $g^*$  to quarks are equal to the Standard Model couplings of the gluon to quarks, except for the presence of an additional  $\sqrt{2}$  factor. Therefore, the gluon excitations appear as wide resonances decaying into pairs of quarks. The width is expected to be

$$\Gamma(g^*) = 2\alpha_s M, \quad (5.1)$$

where  $M$  is the mass of  $g^*$ . This width is of the order of 170 GeV for a mass  $M = 1 \text{ TeV}$ . The production cross-section of these  $g^*$  resonances is complicated, since one has to consider several Feynman diagrams including  $s$ ,  $t$  and  $u$  channels, as discussed in [79] (see Figure 5.2). This complexity requires the use of dedicated Monte Carlo programs, as discussed in [87]. Since in the present analysis only decays to heavy quarks are considered, the production mechanism includes a single

diagram in the  $s$ -channel shown in Figure 5.2(e) ( $q_i \bar{q}_i \rightarrow g^* \rightarrow Q_j \bar{Q}_j$ , where  $q_i$  is a light quark and  $Q_j$  a heavy quark). The cross-section can be computed numerically and the events can be generated in a simple way by modifying the couplings of a heavy gauge boson in the Pythia MC program [22].

The cross-sections obtained in this way are reported in Table 5.1. All cross-sections are computed at leading order (LO). In these computations the energy scale is equal to the mass of the resonance ( $Q^2 = M^2$ ) and CTEQ5L pdf's are selected.

**Table 5.1:** Cross-sections at LHC for  $g^*$  production.

| $M$ (GeV) | $\sigma(g^*)$ (pb) |
|-----------|--------------------|
| 1 000     | 1 109              |
| 1 500     | 192                |
| 2 000     | 47                 |
| 3 000     | 4.9                |

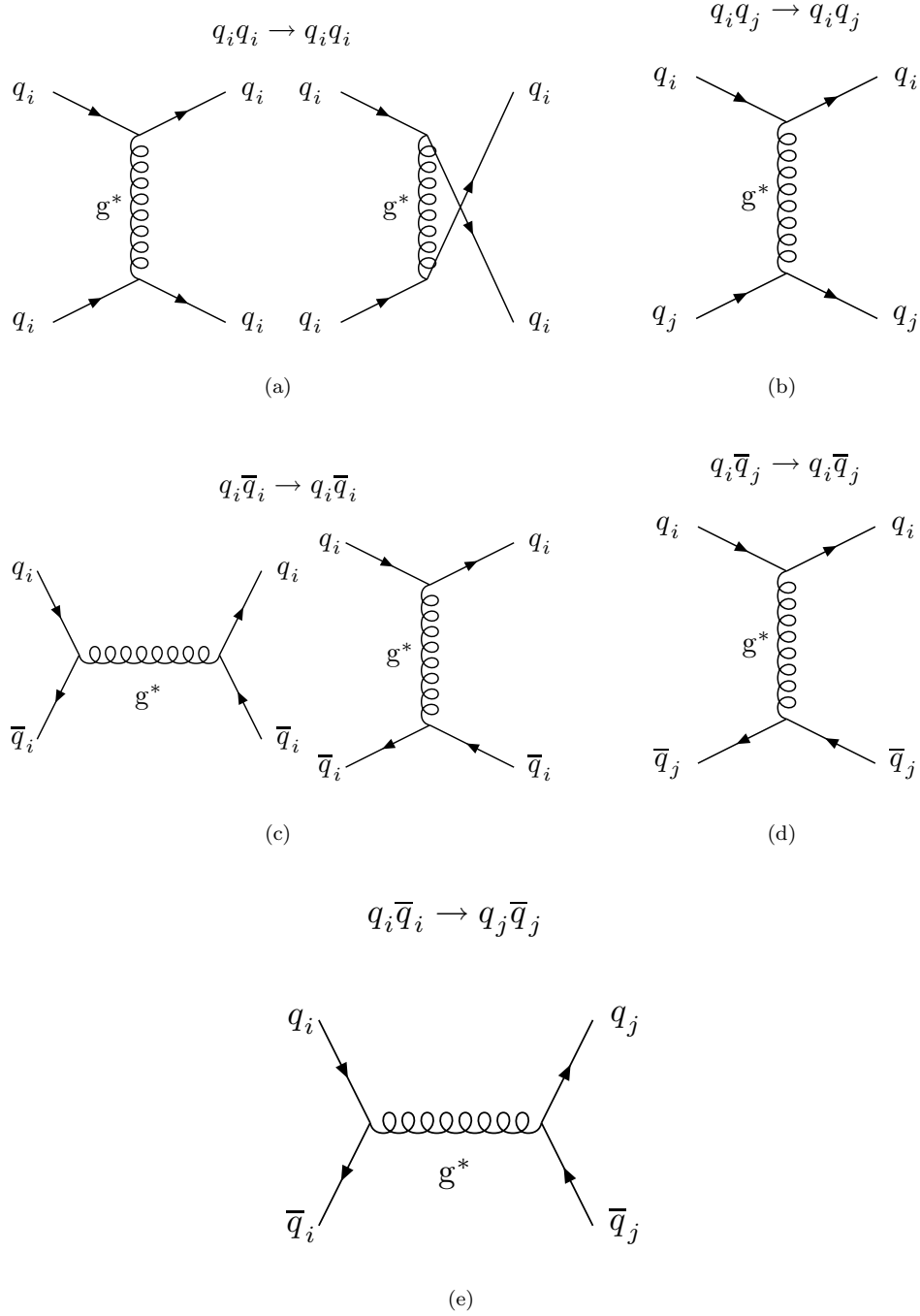
As a consequence of gauge symmetry, all couplings of  $g^*$  to quarks are equal. If the mass of  $g^*$  is large enough, all quark masses can be neglected and the branching ratios ( $\mathcal{BR}$ ) of  $g^*$  to heavy quarks are:

$$\mathcal{BR}(g^* \rightarrow b\bar{b}) = \mathcal{BR}(g^* \rightarrow t\bar{t}) = 1/6 = 16.7\%. \quad (5.2)$$

### 5.2.3 Event Simulation

The analysis presented here is also described in [88].

Most of the events used in the present analysis have been generated using the MC program PYTHIA coupled to ATLFAST [18, 19] to simulate the detector response. The MC program ALPGEN [89] has been used as well to generate



**Figure 5.2:** Feynman diagrams for production of a  $g^*$  decaying into dijets. The indices  $i$  and  $j$  refer to distinct ( $i \neq j$ ) quark flavors.

background events containing  $W + \text{jets}$ . In the ALPGEN MC program, the exact matrix elements are used for multijet production. The following sets of events were used in this analysis:

- **Signal events:**  $g^* \rightarrow b\bar{b}$  and  $t\bar{t}$  with  $g^*$  masses in the range between 1 and 3 TeV.
- **Background events:** Standard Model final states containing  $b\bar{b}$ ,  $t\bar{t}$ , 2 jets and  $W + \text{jets}$ . Since only events with very high  $p_T$  jets and large center of mass energy are relevant in this analysis, it was imposed at the generation level that

$$\sqrt{\hat{s}} > 0.5(1.0) \text{ TeV} \text{ and } \hat{p}_T > 0.1(0.25) \text{ TeV}, \quad (5.3)$$

where  $\sqrt{\hat{s}}$  and  $\hat{p}_T$  are the center-of-mass energy and transverse momentum of the hard process. The low cuts were used in the background estimation for  $M = 1$  and 1.5 TeV and the high cuts for  $M = 2$  and 3 TeV.

Table 5.2 summarizes the number of signal events generated and Table 5.3 the cross-sections and the number of events for background sources. In PYTHIA, dijet events containing light quarks (jj) and heavy quarks ( $b\bar{b}$  and  $t\bar{t}$ ) are generated using different processes. Heavy quarks may appear in the light quark sample as a result of gluon splitting but these events are excluded in the present analysis. Only for the background containing  $W + \text{jets}$  PYTHIA does not provide a reliable estimation, thus we have used the MC program ALPGEN to generate this background using the exact matrix elements for the multijet production.

**Table 5.2:** Number of generated events for  $g^* \rightarrow b\bar{b}$  and  $g^* \rightarrow t\bar{t}$ .

| $M$ (TeV) | $g^* \rightarrow b\bar{b}$ | $g^* \rightarrow t\bar{t}$ |
|-----------|----------------------------|----------------------------|
| 1.0       | 10 000                     | 100 000                    |
| 1.5       | 10 000                     | 30 000                     |
| 2.0       | 10 000                     | 10 000                     |
| 3.0       | —                          | 10 000                     |

**Table 5.3:** Cross-sections and generated events containing  $b\bar{b}$ ,  $jj$ ,  $t\bar{t}$  and  $W$  + jets.

|                        | $\sigma$ (pb) |           | Number of Events |           |
|------------------------|---------------|-----------|------------------|-----------|
|                        | Low cuts      | High cuts | Low cuts         | High cuts |
| $b\bar{b}$             | 391           | 7.7       | 100 000          | 100 000   |
| $jj$                   | 303 000       | 5 700     | 100 000          | 100 000   |
| $t\bar{t}$             | 164           | 6.35      | 100 000          | 100 000   |
| $W$ + jets<br>(ALPGEN) | 161           | 30        | 112 700          | 113 300   |
| $W$ + jets<br>(PYTHIA) | 42.4          | 1.77      | 100 000          | 100 000   |

If KK excitations of  $g$  exist, KK excitations of  $Z$  and  $\gamma$  are also expected and their decays to heavy quarks will reinforce the  $g^*$  signal. Notice that the couplings of the  $g^*$  to quarks are equal to the SM couplings of the gluon (strong process) with an additional factor  $\sqrt{2}$ , however the contribution of KK excitations of  $Z$  and  $\gamma$  are small since they corresponds to electroweak processes and are not considered in the present analysis.

#### 5.2.4 Selection Cuts

For the analysis of the decay  $g^* \rightarrow b\bar{b}$ , the following cuts are applied:

- 2 b-jets with  $|\eta| < 2.5$  and  $p_T$  cuts shown in Table 5.4.

**Table 5.4:** Cuts on  $p_T$  applied to b-jets in the channel  $g^* \rightarrow b\bar{b}$ .

|         | $M = 1 \text{ TeV}$ | $M = 1.5 \text{ TeV}$ | $M = 2 \text{ TeV}$ |
|---------|---------------------|-----------------------|---------------------|
| b-jet 1 | 350 GeV             | 525 GeV               | 700 GeV             |
| b-jet 2 | 150 GeV             | 225 GeV               | 300 GeV             |

The b-tagging of very high  $p_T$  jets is discussed below. Two background sources have been analyzed:  $b\bar{b}$  production (irreducible background) and 2-jet production (reducible background).

For the analysis of the decay  $g^* \rightarrow t\bar{t}$ , the following cuts are applied, assuming that one of the t-quarks decays leptonically and the other hadronically:

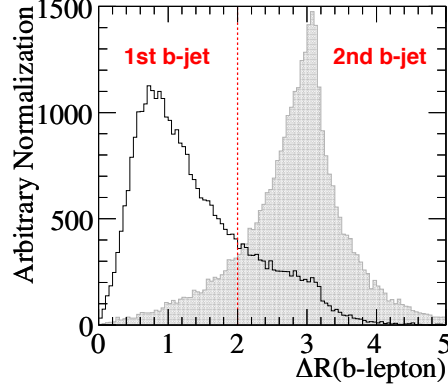
- a lepton (electron or muon) with  $p_T > 25$  GeV and  $|\eta| < 2.5$ , in addition to  $E_T^{\text{miss}} > 25$  GeV. The  $p_T$  on the lepton is necessary for trigger purposes.
- 2 b-jets with  $p_T > 25$  GeV and  $|\eta| < 2.5$ , the first jet such that  $\Delta R(\text{b-lepton}) < 2$  and the second such that  $\Delta R(\text{b-lepton}) > 2$ . The distance  $\Delta R$  is defined in the usual way as

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}, \quad (5.4)$$

where  $\phi$  is the azimuth and  $\eta$  the pseudo-rapidity. With this cut we want to separate the two b-jets in order to reconstruct properly each top quark. Figure 5.3 shows the distribution at parton level of the angular distance  $\Delta R$  between the lepton and the b-jets and the separation obtained with a cut at  $\Delta R = 2$ , for a  $g^*$  mass of 1 TeV. The 1st b-jet ( $\Delta R < 2$ ) comes from the semileptonic decay of one top quark and the 2nd b-jet ( $\Delta R > 2$ ) comes from the hadronic decay of the other top quark. For larger masses of  $g^*$  the discrimination between the two b-jets improves.

- The first t-quark is reconstructed using the first b-jet, the lepton and the missing energy, assuming that the missing neutrino is parallel to the lepton. The second t-quark is reconstructed using the second b-jet and all other reconstructed jets, within a distance of 2. The  $p_T$  of the reconstructed t-quarks should be larger than the cut values reported in Table 5.5 for  $M(g^*) = 1, 1.5, 2$  and 3 TeV.

For the decay  $g^* \rightarrow t\bar{t}$  two background sources have been considered: QCD  $t\bar{t}$  production (irreducible background) and production of  $W + \text{jets}$  (reducible background).



**Figure 5.3:** Distribution of the angular distance ( $\Delta R$ ) between the b-jets and the lepton at parton level for  $M(g^*) = 1$  TeV. The dashed line shows the cut applied to separate the first and the second b-jet.

**Table 5.5:** Cuts on  $p_T$  applied to t-jets in the channel  $g^* \rightarrow t\bar{t}$ .

|         | $M = 1$ TeV | $M = 1.5$ TeV | $M = 2$ TeV | $M = 3$ TeV |
|---------|-------------|---------------|-------------|-------------|
| t-jet 1 | 350 GeV     | 525 GeV       | 700 GeV     | 1 050 GeV   |
| t-jet 2 | 150 GeV     | 225 GeV       | 300 GeV     | 450 GeV     |

The kinematical efficiencies achieved for signal and background events with the selection cuts described before are summarized in Table 5.6 and 5.7. Notice that the kinematical efficiency for the  $g^* \rightarrow t\bar{t}$  decreases strongly with the  $g^*$  mass, this analysis requires isolated leptons according to ATLFAST (leptons separated from jets) and at higher masses the top decay products are more boosted and leptons are no more isolated. This is an artefact of the fast simulation which would not appear in full simulation, and hence the efficiencies are conservatively underestimated.

In all the decays analyzed in this note, the tagging of very high  $p_T$  b-jets is required. The average  $p_T$  of these jets is reported in Table 5.8.



**Table 5.6:** Kinematical efficiencies for the signal ( $\mathcal{BR}$  and tagging efficiencies excluded).

| $M$ (TeV) | $g^* \rightarrow b\bar{b}$ | $g^* \rightarrow t\bar{t}$ |
|-----------|----------------------------|----------------------------|
| 1.0       | 35%                        | 14%                        |
| 1.5       | 32%                        | 12%                        |
| 2.0       | 31%                        | 10%                        |
| 3.0       | —                          | 3%                         |

**Table 5.7:** Kinematical efficiencies for background sources ( $\mathcal{BR}$  and tagging efficiencies excluded).

| $M$ (TeV) | $b\bar{b}$ | $jj$ | $t\bar{t}$ | W + jets |
|-----------|------------|------|------------|----------|
| 1.0       | 4.0%       | 1.7% | 0.40%      | 1.4%     |
| 2.0       | 5.0%       | 2.9% | 0.20%      | 0.9%     |
| 3.0       | —          | —    | 0.013%     | 0.16%    |

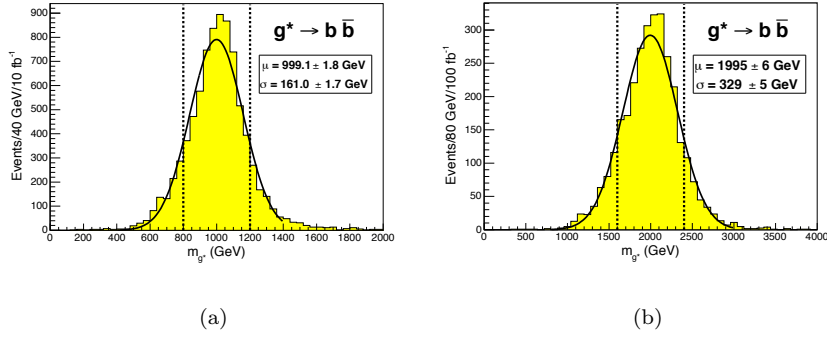
**Table 5.8:** Average  $p_T$  of final state b-jets for the various channels.

| $M$ (TeV) | $\langle p_T \rangle$ (GeV)<br>$g^* \rightarrow b\bar{b}$ | $\langle p_T \rangle$ (GeV)<br>$g^* \rightarrow t\bar{t}$ |
|-----------|-----------------------------------------------------------|-----------------------------------------------------------|
| 1.0       | 400                                                       | 200                                                       |
| 1.5       | 600                                                       | 300                                                       |
| 2.0       | 800                                                       | 400                                                       |
| 3.0       | —                                                         | 600                                                       |

Typical b-jets in most ATLAS analysis have an average  $p_T$  smaller than 200 GeV. For very high  $p_T$  jets, as those relevant in the present analysis, the b-tagging performance is discussed in more detail in [90]. Table 5.9 shows all efficiencies and rejections used in the present analysis.

**Table 5.9:** Efficiencies and rejections applied in the b-tagging analysis.

| $M$ (TeV) | decay      | $\epsilon_b$ | $R_c$ | $R_u$ | decay      | $\epsilon_b$ | $R_c$ | $R_u$ |
|-----------|------------|--------------|-------|-------|------------|--------------|-------|-------|
| 1.0       | $b\bar{b}$ | 0.1          | 100   | 400   | $t\bar{t}$ | 0.5          | 10    | 100   |
| 1.5       | $b\bar{b}$ | 0.1          | 50    | 90    | $t\bar{t}$ | 0.3          | 24    | 200   |
| 2.0       | $b\bar{b}$ | 0.1          | 30    | 50    | $t\bar{t}$ | 0.2          | 30    | 130   |
| 3.0       | $b\bar{b}$ | —            | —     | —     | $t\bar{t}$ | 0.2          | 13    | 30    |

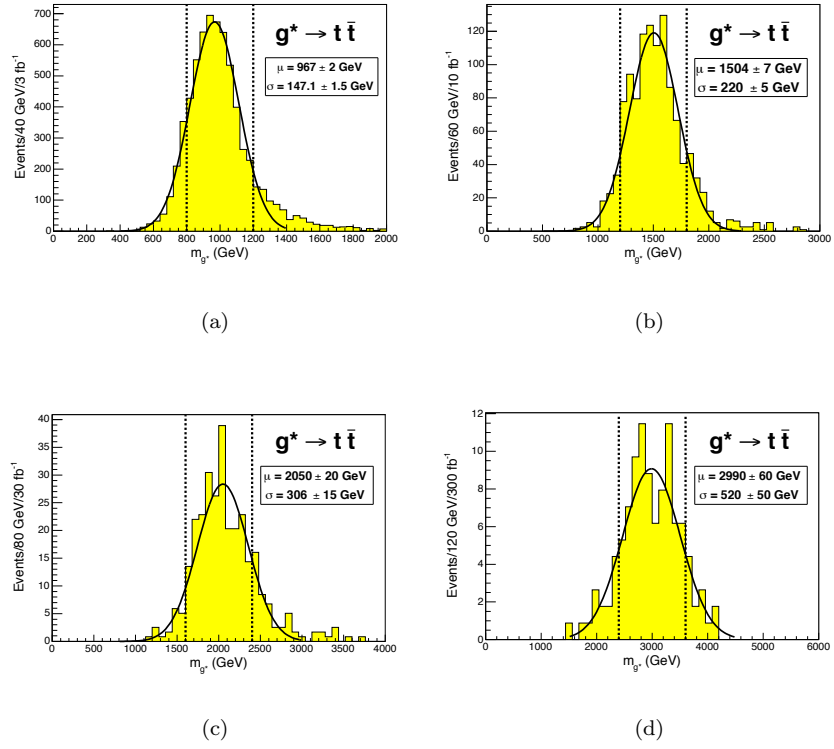


**Figure 5.4:** Reconstructed mass peaks for  $g^* \rightarrow b\bar{b}$  and mass values of  $M = 1$  and 2 TeV. The curves on top of the simulated data are Gaussian fits.

### 5.2.5 Signal and Background

The reconstructed mass peaks are shown in Figures 5.4(a) and 5.4(b), for the b-quark channel, and in Figures 5.5(a) to 5.5(d), for the t-quark channel. The corresponding mean values and widths resulting from Gaussian fits are reported in Table 5.10.

Since the natural width of  $g^*$  is around 170 GeV for  $M = 1$  TeV, both the natural width and experimental effects (fragmentation and detector resolution) contribute to the mass peak, and these contributions are approximately equal.



**Figure 5.5:** Reconstructed mass peaks for  $g^* \rightarrow t\bar{t}$  and mass values of  $M = 1, 1.5, 2$  and  $3$  TeV. The curves on top of the simulated data are Gaussian fits.

**Table 5.10:** Central value of the reconstructed mass ( $M$ ) and width ( $\pm \Delta M$ ) for the various decay channels analyzed. All values are in GeV.

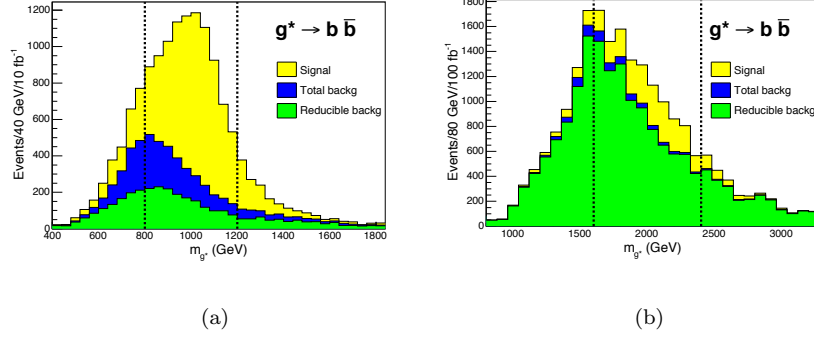
| $M$ (TeV) | $g^* \rightarrow b\bar{b}$ | $g^* \rightarrow t\bar{t}$ |
|-----------|----------------------------|----------------------------|
| 1.0       | $999 \pm 161$              | $967 \pm 147$              |
| 1.5       | $1\,504 \pm 254$           | $1\,504 \pm 220$           |
| 2.0       | $1\,995 \pm 329$           | $2\,050 \pm 306$           |
| 3.0       | —                          | $2\,990 \pm 520$           |

Figures 5.6 and 5.7 display the invariant mass distributions, including the signal on top of the expected background. By applying mass cuts of  $\pm 200$ ,  $\pm 300$ ,  $\pm 400$  and  $\pm 600$  GeV around the expected mass values of  $M = 1, 1.5, 2$  and  $3$  TeV, respectively, it is possible to obtain the number of signal and background events which are reported in Tables 5.11 and 5.12, for an integrated luminosity of  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ , corresponding to 3 years of running of high luminosity. The number of expected events for the signal and the irreducible background are calculated according to

$$N = \mathcal{L} \cdot \sigma \cdot \mathcal{BR} \cdot \epsilon_{\text{kin}} \cdot \epsilon_{\ell} \cdot \epsilon_b^2, \quad (5.5)$$

assuming that the various efficiencies are independent since the b-tagging efficiency already takes into account the dependency with  $\epsilon_{\text{kin}}$  and the other dependencies should be negligible.  $\mathcal{L}$  is the luminosity,  $\sigma$  is the cross section of the process and  $\mathcal{BR}$  is the branching ratio of the whole decay process. For  $g^* \rightarrow b\bar{b}$  the branching ratio is 16%, whereas for  $g^* \rightarrow t\bar{t} \rightarrow \ell\nu jj b\bar{b}$  it is 4.5% after including top semileptonic decays. For the background the semileptonic decay is included in the kinematical efficiency  $\epsilon_{\text{kin}}$  (shown in Table 5.6 and 5.7). Finally,  $\epsilon_{\ell}$  is the lepton tagging efficiency of 0.9 and  $\epsilon_b$  is the b-tagging efficiency shown in Table 5.9. For the reducible background the formula is similar but the b-tagging efficiency squared ( $\epsilon_b^2$ ) is replaced by the dijet efficiency:

$$\epsilon_{\text{qq}} = n_{bb}\epsilon_b^2 + n_{bc}\frac{\epsilon_b}{R_c} + n_{bu}\frac{\epsilon_b}{R_u} + \frac{n_{uc}}{R_u R_c} + \frac{n_{uu}}{R_u^2} + \frac{n_{cc}}{R_c^2}, \quad (5.6)$$



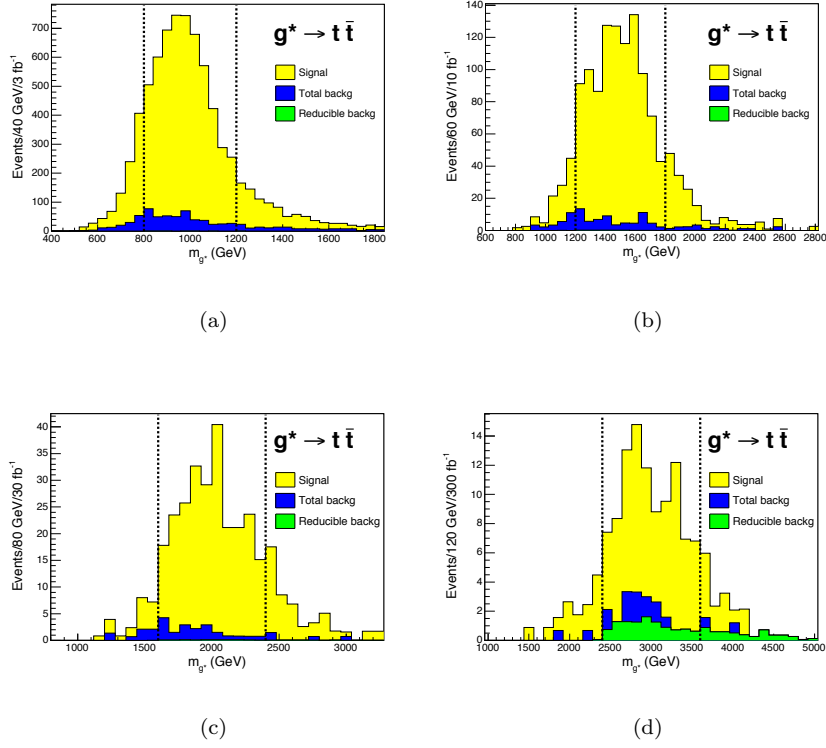
**Figure 5.6:** Reconstructed mass peaks for  $g^* \rightarrow b\bar{b}$  including both signal and background contributions for mass values of  $M = 1$  and 2 TeV. The mass window used to calculate the significance is indicated in the figures. Luminosities of  $\mathcal{L} = 10^4 \text{ pb}^{-1}$  and  $\mathcal{L} = 10^5 \text{ pb}^{-1}$  are assumed for  $M = 1$  and 2 TeV, respectively.

where  $n_{ii}$  is the fraction of jet pairs of type  $ii$ . The various efficiencies and rejections are shown in Table 5.9.

The significance of the expected signal is defined as

$$\text{Significance} = \frac{N_{\text{signal}}}{\sqrt{N_{\text{bkg}}}}, \quad (5.7)$$

for  $N_{\text{signal}} \geq 50$ , which is the case in the present analysis, and it is presented in Tables 5.11 and 5.12. In the  $g^* \rightarrow t\bar{t}$  channel, the reducible background is composed of  $W$  + jets events. This background can be calculated using both PYTHIA and ALPGEN. The values obtained with ALPGEN are considerably larger and have been used, in a conservative approach, to calculate the various significances. However in this analysis the  $W$  + jets background is significantly smaller than the  $t\bar{t}$  background.



**Figure 5.7:** Reconstructed mass peaks for  $g^* \rightarrow t\bar{t}$  including both signal and background contributions for mass values of  $M = 1, 1.5, 2$  and  $3$  TeV. The mass window used to calculate the significance is indicated in the figures. Luminosities of  $\mathcal{L} = 3 \times 10^3 \text{ pb}^{-1}$ ,  $\mathcal{L} = 10^4 \text{ pb}^{-1}$ ,  $\mathcal{L} = 3 \times 10^4 \text{ pb}^{-1}$  and  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ , are assumed for  $M = 1, 1.5, 2$  and  $3$  TeV, respectively.

**Table 5.11:** Signal and background for  $g^* \rightarrow b\bar{b}$  assuming  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ .

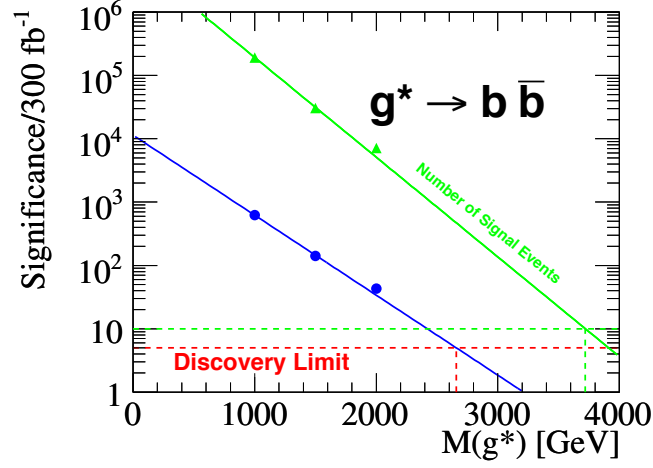
| $M \text{ (TeV)}$ | Signal  | Irreducible bkg | Reducible bkg | Significance |
|-------------------|---------|-----------------|---------------|--------------|
| 1.0               | 192 412 | 48 562          | 47 099        | 622          |
| 1.5               | 30 720  | 6 018           | 41 394        | 141          |
| 2.0               | 7 168   | 1 174           | 26 970        | 43           |

**Table 5.12:** Signal and background for  $g^* \rightarrow t\bar{t}$  assuming  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ .

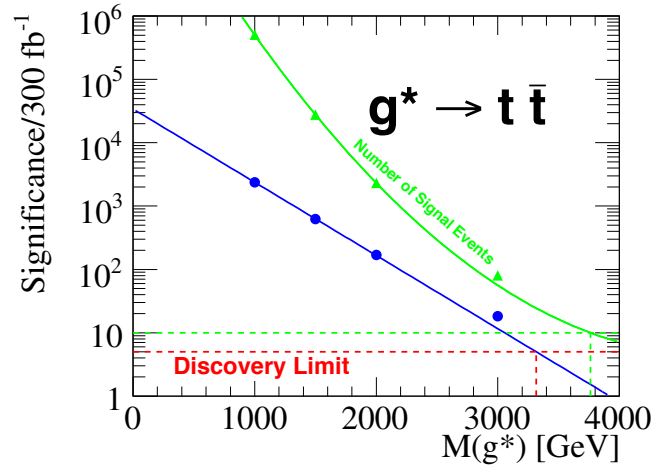
| $M \text{ (TeV)}$ | Signal  | Irreducible bkg | Reducible bkg (ALPGEN) | Reducible bkg (PYTHIA) | Significance (ALPGEN) |
|-------------------|---------|-----------------|------------------------|------------------------|-----------------------|
| 1.0               | 505 413 | 44 612          | 493                    | 48                     | 2 379                 |
| 1.5               | 27 838  | 1 926           | 52                     | 1.77                   | 626                   |
| 2.0               | 2 318   | 174             | 12                     | 1.01                   | 170                   |
| 3.0               | 80.3    | 8.9             | 10.5                   | 0.95                   | 18.2                  |

Figures 5.8 and 5.9 show the significance as a function of the  $g^*$  mass. Assuming an exponential dependence of the significance on the mass, it is possible to conclude that a significance of 5 may be achieved below  $M = 2.7 \text{ TeV}$  and  $M = 3.3 \text{ TeV}$ , for  $g^* \rightarrow b\bar{b}$  and  $t\bar{t}$ , respectively. On the other hand, it is not possible in general to obtain mass peaks well separated from the background. Therefore, it is unlikely that an excess of events in the channel  $g^* \rightarrow b\bar{b}$  could be used as an evidence for the presence of the  $g^*$  resonance, since there are large uncertainties in the calculation of the backgrounds. For  $M = 1 \text{ TeV}$ , the peak displacement (see Figure 5.6(a)) could be used as an evidence for new physics if the b-jet energy scale can be accurately computed.

In the  $g^* \rightarrow t\bar{t}$  case, on the contrary, the background is mainly irreducible ( $t\bar{t}$  production) which is better understood and not so large, so the  $g^*$  resonance can be detected in this decay channel if the  $t\bar{t}$  cross-section can be computed in a reliable way.



**Figure 5.8:** Significance as a function of mass for  $g^* \rightarrow b\bar{b}$  and a luminosity of  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ . An exponential curve is fitted to the calculated values.



**Figure 5.9:** Significance as a function of mass for  $g^* \rightarrow t\bar{t}$  and a luminosity of  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ . An exponential curve is fitted to the calculated values.



### 5.2.6 Summary

The decays  $g^* \rightarrow b\bar{b}$  and  $g^* \rightarrow t\bar{t}$  have been investigated using the simulation program ATLFAST for  $g^*$  masses in the range between 1 and 3 TeV. The analysis of expected signals and backgrounds shows that the decays into b-quarks are difficult to detect, but the decays into t-quarks, on the contrary, might yield a significant signal for the  $g^*$  mass below 3.3 TeV. This signal could be used to confirm the presence of  $g^*$ , in case that an excess of events is observed in the dijet cross-section as proposed in [79].

## 5.3 Top Polarization

### 5.3.1 Introduction

In previous sections we have studied the ATLAS potential to discover a heavy resonance of the gluon using its hadronic decay to heavy quarks. This resonance is predicted by a ED model with a flat extra dimension of size  $\text{TeV}^{-1}$  ( $\text{TeV}^{-1}$  ED model in the following). However, there are other models predicting a similar resonance of the gluon, like the recent Randall-Sundrum model [81,82] with a single warped extra dimension (RS model in the following). In this case it is useful to study other properties of the process, apart from the invariant mass distributions. We propose here to study top polarization in the decays of  $g^*$  to tops and use it to discriminate the various models.

### 5.3.2 Top polarization in heavy resonance decays

A typical Feynman diagram for the production at the LHC of top quarks in the decay of a heavy neutral resonance  $R$  is shown in Figure 5.10. This resonance,  $R$  could be  $Z_H$  or  $g^*$ . The coupling of a vectorial resonance  $R$  to top quark pairs is of the type:

$$g\bar{t}\gamma^\mu(v_t - a_t\gamma_5)tR_\mu, \quad (5.8)$$

where  $t$  is the top quark Dirac spinor,  $R_\mu$  is the resonance vectorial field,  $g$  is the coupling constant and finally  $v_t$  and  $a_t$  are the vector and axial vector couplings of the resonance to top quarks. It can be shown that the resulting top quarks are polarized, and that the average longitudinal polarization is [91, 92]:

$$\langle P_L \rangle = -\frac{2v_t a_t \beta}{(v_t^2 + a_t^2)\beta^2 + \frac{3}{2}v_t^2(1 - \beta^2)}, \quad (5.9)$$

where  $\beta$  is the top-quark velocity in the rest frame of the resonance. Figure 5.11 shows the average top polarization as a function of the ratio  $r_t = a_t/v_t$  for different values of  $\beta$ .

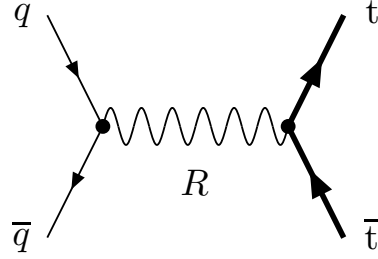
In pure V-A theories (this is the case of  $Z_H$  in Little Higgs models),  $v_t = a_t = 1$  and therefore

$$\langle P_L \rangle = -\frac{4\beta}{3 + \beta^2} \rightarrow -1 \quad \text{for } \beta \rightarrow 1, \quad (5.10)$$

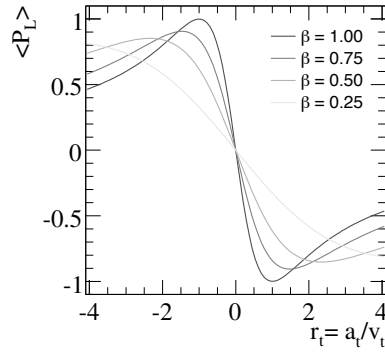
and as a result  $\langle P_L \rangle$  grows asymptotically to  $-1$  (left-handed top quarks) as  $\beta \rightarrow 1$  (*i.e.*, as the mass of the resonance increases). The average longitudinal polarization  $\langle P_L \rangle$  is plotted as a function of the resonance mass  $m_R$  in Figure 5.12, assuming a pure V-A theory. This figure shows that  $\langle P_L \rangle$  is very close to the asymptotic value of  $-1$  for masses above 1 TeV. For  $\beta \approx 1$  and arbitrary couplings, the polarization is

$$\langle P_L \rangle = -A_t = -\frac{2v_t a_t}{v_t^2 + a_t^2}. \quad (5.11)$$

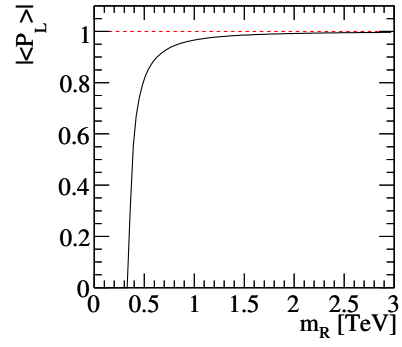
This formula is similar to the formula of  $\tau$  polarization in  $Z$  decays, that has been used by LEP experiments [93]. If the resonance  $R$  is coupled to top quarks via a purely vectorial coupling (this being the case of  $g^*$  for the  $\text{TeV}^{-1}$  ED model discussed before), the resulting top quarks are unpolarized. It is noted finally that top quark pairs produced at the LHC in SM processes, gluon-gluon or quark-antiquark fusion, are on the average unpolarized. It is possible however to measure spin correlations as discussed for example in [94].



**Figure 5.10:** Feynman diagram showing a heavy resonance decaying into top quarks.



**Figure 5.11:** Average top polarization as a function the ratio  $a_t/v_t$  for different values of the top quark velocity,  $\beta$ , in the rest frame of the resonance.



**Figure 5.12:** Average top polarization as a function of resonance mass for a pure V-A theory.

### 5.3.3 Observables for top polarization

Top quarks decay with a branching ratio of nearly 100% into a b-quark and a W boson. It is assumed in the following that the W boson decays leptonically into an electron or a muon. The analysis of the angular distributions of the decay products, in the top rest frame, allows the determination of the longitudinal top polarization, as discussed for example in [95]. This angular distribution is:

$$\frac{dN}{d\cos\theta^*} = \frac{N_0}{2}(1 + hS\cos\theta^*), \quad (5.12)$$

where  $N$  is the number of events,  $N_0$  is a normalization constant,  $\theta^*$  is the polar angle of the decay product (W or lepton) in the top rest frame (the  $z$  axis being the top direction in the  $R$  rest frame),  $S$  is the top polarization ( $-1 < S < +1$ ) and finally  $h$  is a constant. The value of  $h$  is

$$h = 1 \quad \text{and} \quad h = \frac{1 - 2(m_W/m_t)^2}{1 + 2(m_W/m_t)^2} \approx 0.41, \quad (5.13)$$

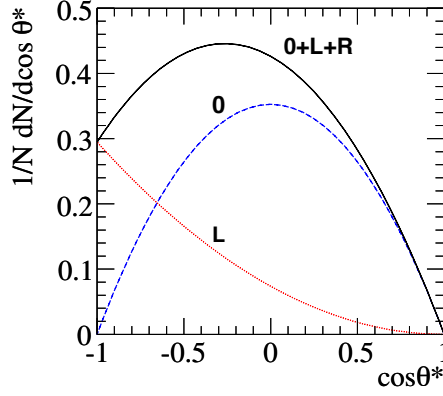
for leptons and W bosons, respectively. This result shows that the lepton is a more sensitive top polarization analyser than the W boson.

For completeness, it is interesting to mention that whether the top quark is polarized or not, the W boson from top decays is always polarized. More precisely, the angular distribution of the lepton in the W rest frame (the  $z$  axis being the W direction in the top rest frame) is:

$$\frac{dN}{d\cos\theta^*} = N_0 \left[ F_0 \left( \frac{\sin\theta^*}{\sqrt{2}} \right)^2 + F_L \left( \frac{1 - \cos\theta^*}{2} \right)^2 + F_R \left( \frac{1 + \cos\theta^*}{2} \right)^2 \right], \quad (5.14)$$

where  $N$  is the number of events,  $N_0$  is a normalization constant, and  $F_0$ ,  $F_L$  and  $F_R$  are the amplitudes corresponding to longitudinal, left-handed and right-handed W boson, respectively (or equivalently, helicities  $\Lambda = 0$ ,  $\Lambda = -1$  and  $\Lambda = +1$ ). These amplitudes have the following values:

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} \approx 0.70 \quad , \quad F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} \approx 0.30 \quad \text{and} \quad F_R = 0, \quad (5.15)$$



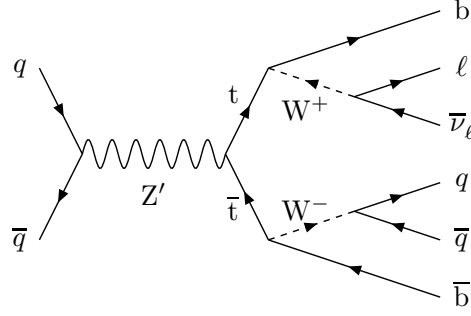
**Figure 5.13:** Angular distribution of the lepton in the W rest frame, with  $z$  axis along the W direction in the top rest frame.

implying that right-handed W bosons are not allowed in SM decays of top quarks. The distribution  $dN/d\cos\theta^*$  for W decays into leptons, shown in Figure 5.13, can be measured at the LHC as discussed for example in [94], and used to extract a measurement of the top quark mass. From the point of view of top polarization, this distribution is not useful, but may serve to check Monte Carlo (MC) generators, as discussed below.

### 5.3.4 Monte Carlo Generators

In this analysis, events of the type shown in Figure 5.14 are required. In these events, a heavy resonance  $Z'$  is produced in quark-antiquark annihilation and decays into a top-antitop pair. Such processes are available in PYTHIA [22], but in this MC generator top quarks are unpolarized. For this reason PYTHIA is not useful in the present analysis to study signal events. In order to have a correct simulation of top polarization, the full  $2 \rightarrow 6$  matrix element, *i.e.* the matrix element of the process

$$q\bar{q} \rightarrow Z' \rightarrow b\bar{b}\ell\bar{\nu}_\ell q\bar{q} \quad (5.16)$$



**Figure 5.14:** The complete  $2 \rightarrow 6$  process to be simulated by MC in order to obtain the correct top polarization.

has to be computed and implemented inside the MC generator. This goal has been achieved using the ACER MC generator [96].

The following cases have been simulated:

- $Z'$  with pure  $V-A$  couplings to fermions and
- $Z'$  with pure  $V+A$  couplings to fermions.

In each case, 20 000 events were generated with  $M(Z') = 1$  TeV. Table 5.13 shows the vector and axial vector couplings used in these simulations. In Figures 5.15 and 5.16 various distributions used to validate the MC are displayed. Each figure shows the following 4 distributions obtained at the parton level:

- a) lepton polar distribution in the  $W$  boson rest frame, the  $z$  axis being along the direction of the  $W$  boson in the lab frame,
- b) lepton polar distribution in the  $W$  boson rest frame, the  $z$  axis being along the direction of the  $W$  in the top rest frame,
- c)  $W$  boson polar distribution in the top quark rest frame, the  $z$  axis being along the direction of the top quark in the  $Z'$  rest frame, and finally

- d) lepton polar distribution in the top quark rest frame, the  $z$  axis being along the direction of the top quark in the  $Z'$  rest frame.

Figures a) and b) are not useful to analyse top polarization. As commented before, figure b) is however useful to analyse W boson polarization and to check the MC generator. On the contrary, figures c) and d) both allow the determination of top polarization, although figure d) is more sensitive, as discussed before.

**Table 5.13:** Parameters used for top polarization analysis.

| $Z'$  | $v_t$ | $a_t$ | $< P_L >$ |
|-------|-------|-------|-----------|
| $Z_L$ | +1    | +1    | -1        |
| $Z_R$ | +1    | -1    | +1        |

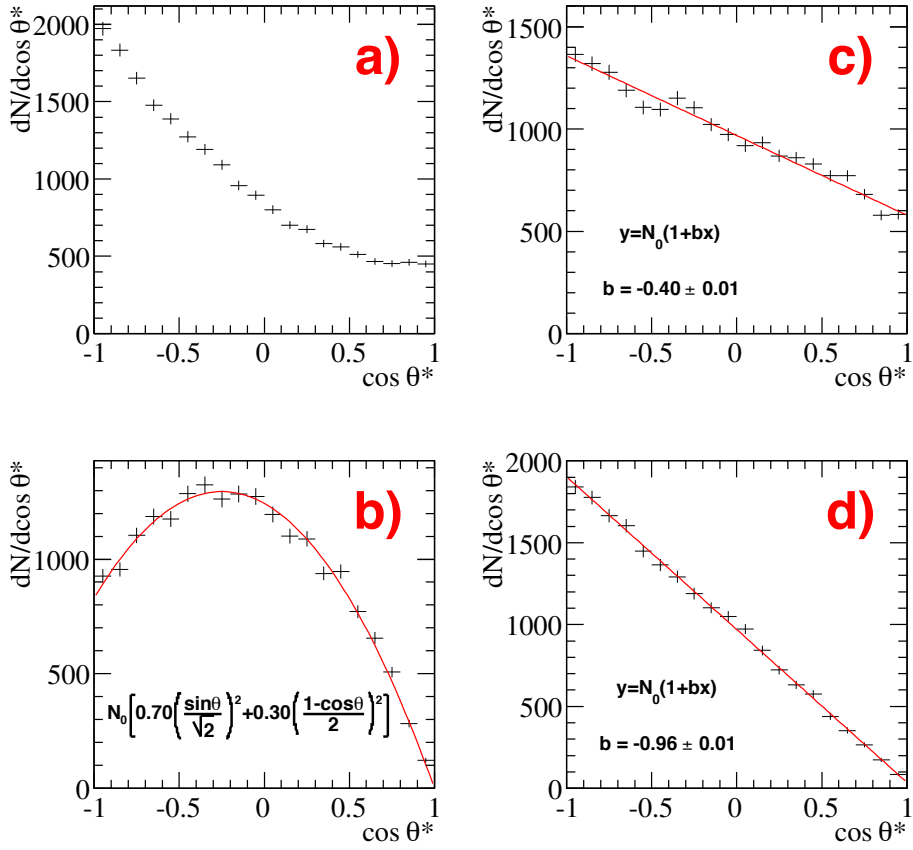
Finally, Figure 5.17 shows the value of  $S$ , obtained from a fit of plot d), as a function of the ratio  $r_t = a_t/v_t$ . The MC values are in good agreement with the theoretical formula discussed before:

$$S = -\frac{2r_t\beta}{(1+r_t^2)\beta^2 + \frac{3}{2}(1-\beta^2)}, \quad (5.17)$$

where  $\beta = 0.94$  is the top quark velocity corresponding to the decay of a 1 TeV resonance.

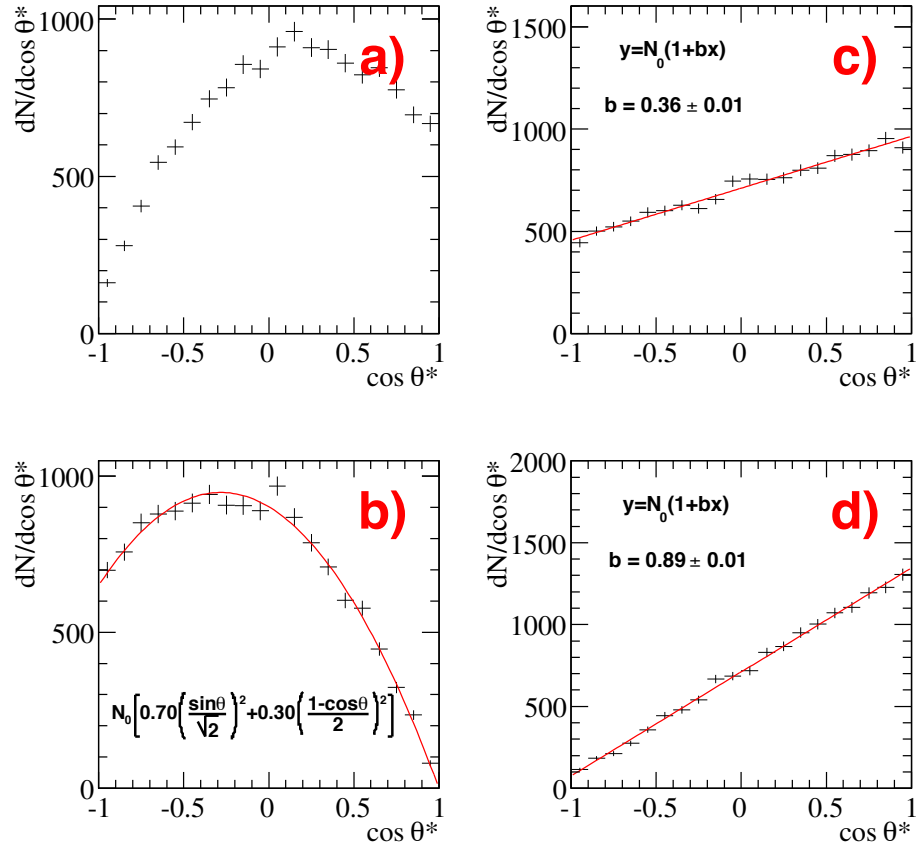
### 5.3.5 Application to Randall-Sundrum KK gluons

In reference [88], the search for a Kaluza-Klein excitation of the gluon in a model with a flat extra dimension of size  $1 \text{ TeV}^{-1}$  is discussed (the  $\text{TeV}^{-1}$  ED model). In this model, the excited gluon  $g^*$  decays to all quarks with equal probability and the decay particles are unpolarized. A different model has recently been proposed [81, 82] within the framework of the so-called Randall-Sundrum (RS) scenario, with a single warped extra dimension (RS model). In the original RS model, SM particles are confined to a single brane. However, models with all

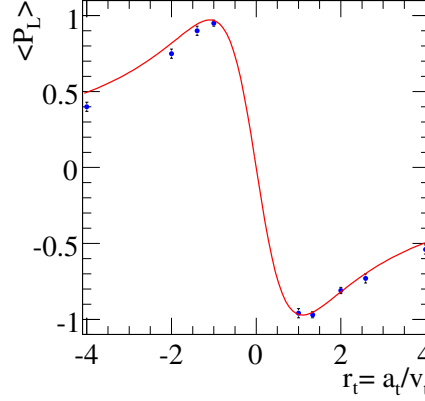


**Figure 5.15:** Polarization plots at the parton level for a pure V–A theory. The angle  $\theta^*$  is defined in the text for each figure. These plots are obtained at the parton level using 20 000 signal events.





**Figure 5.16:** Polarization plots at the parton level for a pure V+A theory. The angle  $\theta^*$  is defined in the text for each figure. These plots are obtained at the parton level using 20 000 signal events.



**Figure 5.17:** Top quark polarization as a function of  $r_t$ . The theoretical curve (with  $\beta = 0.94$ ) is shown on top of the MC values.

particles propagating through all 5 dimensions, like the one proposed in [81, 82], can have attractive features such as explaining the fermion mass hierarchy and allowing for coupling unification.

A distinctive feature of the model proposed in [81, 82] is that decays into top quarks are dominant and that these top quarks are polarized. Gluon KK states are coupled to quarks in the way:

$$g_s \bar{q} \gamma^\mu (v_q - a_q \gamma_5) q g_\mu^*, \quad (5.18)$$

where  $q$  is the quark field,  $g_\mu^*$  the KK-gluon vectorial field,  $g_s$  the strong coupling constant and finally  $v_q$  and  $a_q$  are vector and axial vector couplings. Table 5.15 provides the values of  $v_q$  and  $a_q$  for all quarks, together with the expected polarization. Using these couplings it is possible to calculate  $g^*$  decays and production rates. The cross-section for  $g^*$  production at the LHC is shown in Table 5.14. Furthermore, the width of the  $g^*$  resonance is  $\Gamma/M \approx 0.17$ , so  $g^*$  is a wide resonance with a similar width as the excited gluon discussed before from the  $\text{TeV}^{-1}$  ED model. The difference is that now the decay into top quark pairs is dominant, since  $\mathcal{BR}(g^* \rightarrow t\bar{t}) = 92.5\%$ , and top quarks are polarized as shown in Table 5.15.

**Table 5.14:** Cross-section of  $g^*$  production in the RS model at the LHC.

| $M$ (GeV) | $\sigma(g^*)$ (pb) |
|-----------|--------------------|
| 1 000     | 30                 |
| 1 500     | 7.8                |
| 2 000     | 2.2                |
| 3 000     | 0.3                |

**Table 5.15:** Parameters of the RS model.

| quark | $v_q$ | $a_q$ | $\langle P_L \rangle$ |
|-------|-------|-------|-----------------------|
| u, c  | 0.2   | 0.0   | 0.0                   |
| d, s  | 0.2   | 0.0   | 0.0                   |
| b     | 0.6   | 0.4   | -0.92                 |
| t     | 2.5   | -1.5  | +0.88                 |

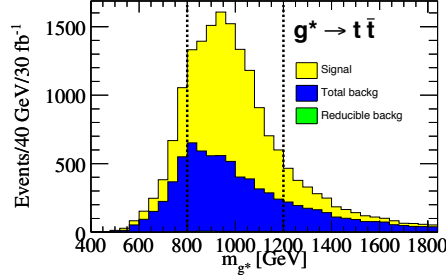
### 5.3.6 Event Analysis

In order to analyse detector effects and backgrounds, the following event samples have been generated using PYTHIA coupled to ATLFAST:

- **Signal events:** 200 000 events  $g^* \rightarrow t\bar{t}$ , assuming a mass of 1 TeV for the excited gluon  $g^*$ .
- **Background events:** 1 million events  $pp \rightarrow t\bar{t}X$  with  $\sqrt{\hat{s}} > 0.5$  TeV and  $\hat{p}_T > 0.1$  TeV,  $\sqrt{\hat{s}}$  and  $\hat{p}_T$  being the center-of-mass energy and the transverse momentum of the hard process, respectively.

These MC samples are such that statistical fluctuations correspond to an integrated luminosity of about  $\mathcal{L} = 30 \text{ fb}^{-1}$  (3 years of LHC running at low luminosity) once the b-tagging is taken into account <sup>1</sup>. As commented before, top quarks are

<sup>1</sup>Since b-tagging is not included in ATLFAST, the number of events needed is reduced a factor of 4 for a b-tagging efficiency of 0.5.



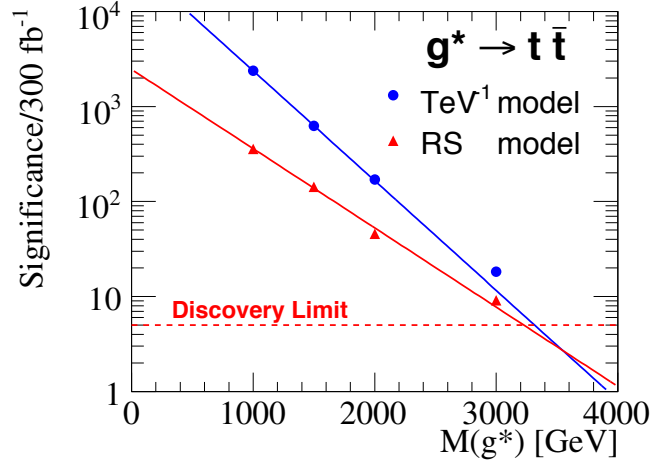
**Figure 5.18:** Invariant mass distribution for the expected signal and background for a 1 TeV RS excited gluon, assuming an integrated luminosity of  $30 \text{ fb}^{-1}$ .

not polarized in PYTHIA. For signal events, this does not matter as long as the aim of the study is to analyse detector effects. These samples were already used in the analysis presented for the  $\text{TeV}^{-1}$  ED model. The event selection proceeds also in the same way, it can be found in section 5.2.4.

Table 5.16 shows the expected signal and background inside a mass window of  $\pm 200 \text{ GeV}$  around  $M = 1 \text{ TeV}$ , assuming an integrated luminosity of  $\mathcal{L} = 30 \text{ fb}^{-1}$ . The number of events is calculated following Equation 5.5. As observed in the first analysis, all backgrounds apart from irreducible  $t\bar{t}$  events are negligible. Figure 5.18 shows the simulated signal on top of the background. The significance, defined in Equation 5.7, is large and signal extraction seems possible, provided that the systematic error in the estimation of the background is not too large. The b-tagging efficiencies and rejections used are shown in Table 5.9. The average  $p_T$  of the b-jets is  $200 \text{ GeV}$ .

**Table 5.16:** Expected signal and background.

| Luminosity<br>( $\text{fb}^{-1}$ ) | Signal<br>(PYTHIA) | Irreducible bkg.<br>$t\bar{t}$ (PYTHIA) | Significance |
|------------------------------------|--------------------|-----------------------------------------|--------------|
| 30.                                | 7 581              | 4 461                                   | 113          |

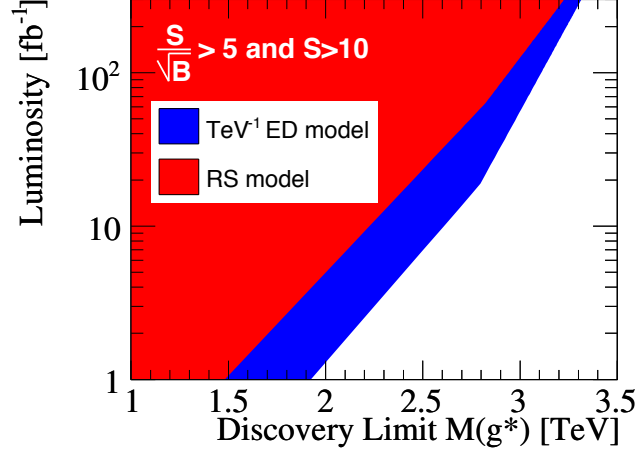


**Figure 5.19:** Significance as a function of the  $g^*$  mass for an integrated luminosity of  $\mathcal{L} = 300 \text{ fb}^{-1}$ .

Figure 5.19 shows the significance as a function of the  $g^*$  mass for a luminosity of  $\mathcal{L} = 300 \text{ fb}^{-1}$ . The circles correspond to the  $\text{TeV}^{-1}$  ED model and the triangles to the new RS model. The discovery limit at significance equal 5 is 3.3 TeV and 3.2 TeV for the  $\text{TeV}^{-1}$  ED model and RS model respectively. Figure 5.20 shows the luminosity needed in order to discover a gluon resonance as a function of the  $g^*$  mass. The excluded regions have been obtained by requiring significances larger than 5 and number of signal events larger than 10.

### 5.3.7 Top reconstruction

A correct reconstruction of the decay  $t \rightarrow bW \rightarrow b\ell\nu$  is important since the measurement of top polarization relies on the angles between the various decay products. The problem is of course the reconstruction of the neutrino direction, since the missing energy in the transverse plane provides only 2 out of 3 components of the neutrino momentum. It is well known, however, that the longitudinal momentum of the neutrino can be calculated from the equation (assuming that



**Figure 5.20:** Minimum luminosity required to observe a  $g^*$  decaying into tops, as a function of the  $g^*$  mass.

the lepton is an electron)

$$m_W^2 = (p_e + p_\nu)^2, \quad (5.19)$$

where  $p_e$  and  $p_\nu$  are the 4-momenta of the electron and the neutrino, respectively. Expanding this equation, a quadratic equation on the longitudinal neutrino momentum is obtained

$$(p_T^e)^2 (p_z^\nu)^2 - 2A p_z^e p_z^\nu + (E^e)^2 (p_T^\nu)^2 - A^2 = 0, \quad (5.20)$$

where  $A = m_W^2/2 + \mathbf{p}_T^e \cdot \mathbf{p}_T^\nu$ . This equation has 2 solutions, namely

$$p_z^\nu = \frac{A p_z^e}{(p_T^e)^2} \pm \frac{E^e}{(p_T^e)^2} \sqrt{A^2 - (p_T^e p_T^\nu)^2}. \quad (5.21)$$

In the limit  $m_W \rightarrow 0$ , the only physical solution is such that  $\mathbf{p}_T^e \cdot \mathbf{p}_T^\nu = p_T^e p_T^\nu$ , *i.e.* the neutrino is parallel to the electron, as expected in the decay of a massless particle, and the second term vanishes. This solution turns out to be a good

solution, provided the resonance  $g^*$  is heavy enough. Moreover, the introduction of the second term is problematic for two reasons:

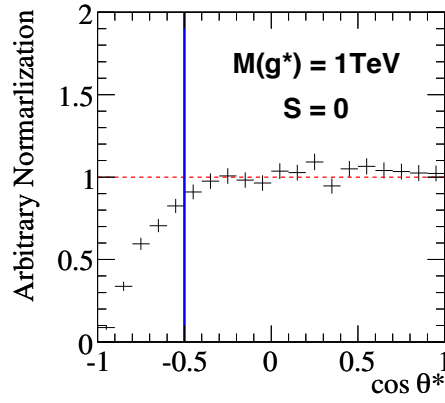
- a) the term under the square root may be negative, yielding an unphysical solution,
- b) there are two solutions in any case, and there is no simple way to decide which one is correct.

In the following, only the first term is used to calculate the longitudinal momentum of the neutrino.

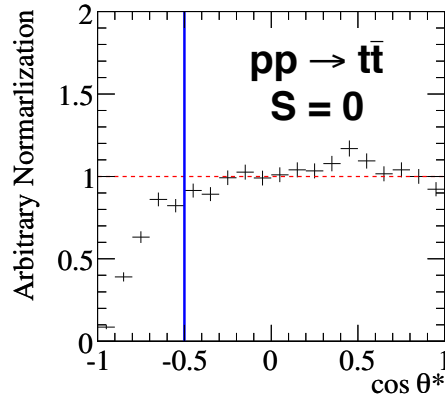
### 5.3.8 Measurement of top polarization

Once the neutrino momentum is reconstructed, the top quark momentum and energy can be calculated, and all decay products can be boosted to the top rest frame. As discussed before, the most interesting variable to analyse top polarization is the polar angle of the lepton in this top rest frame. The distribution obtained, after selection cuts, using the  $g^* \rightarrow t\bar{t}$  sample generated with PYTHIA/ATLFAST is displayed in Figure 5.21. The distribution should be flat since there is no polarization in PYTHIA. A large distortion is observed for  $\cos\theta^* < -0.5$  but the distribution is otherwise flat. Therefore the region  $-0.5 < \cos\theta^* < 1$  can be safely used to extract top polarization. The same distribution is obtained for the background of Standard Model top events, as shown in Figure 5.22. The drop in acceptance observed for  $\cos\theta^* < -0.5$  is introduced by the  $p_T$  cuts, imposed by the trigger selections, and is therefore unavoidable.

The statistical uncertainty in the measurement of top polarization is a function of the luminosity. An additional error in the polarization is expected from the normalization of the total background. In the following we assume that the systematic uncertainty on the background is 20% (a better estimation should result from a detailed study of the uncertainty in the calculation of the SM top production cross-section). The main contribution to the total background comes from the irreducible background,  $t\bar{t}$ , since the reducible background of  $W + \text{jets}$

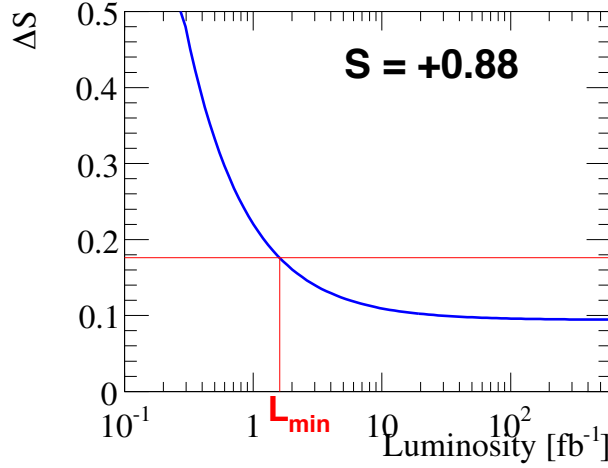


**Figure 5.21:** Distribution of the lepton polar angle in the top rest frame, using  $g^* \rightarrow t\bar{t}$  events generated with PYTHIA for  $M(g^*) = 1\text{ TeV}$ , and after applying selection cuts.



**Figure 5.22:** Distribution of the lepton polar angle in the top rest frame, using Standard Model  $t\bar{t}$  events generated with PYTHIA, and after applying selection cuts.



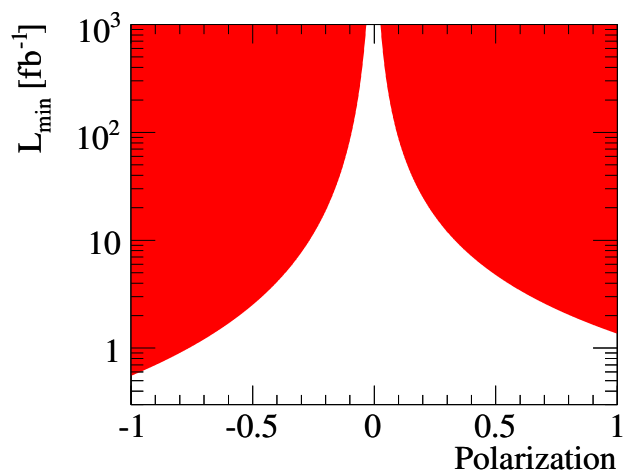


**Figure 5.23:** Uncertainty in the measurement of top polarization as a function of the luminosity.

is negligible here. The total error  $\Delta S$  in the polarization measurement (including the cut  $\cos \theta^* > -0.5$ ) is displayed as a function of the luminosity in Figure 5.23. In the RS model that has been considered before, the expected top polarization is  $S = +0.88$ , therefore  $S - 5\Delta S$  is positive for  $\Delta S < 0.18$ , or equivalently for a luminosity  $\mathcal{L} > \mathcal{L}_{\min}$  with  $\mathcal{L}_{\min} \approx 2 \text{ fb}^{-1}$ . The value of  $\mathcal{L}_{\min}$  can be interpreted as the minimum luminosity required to prove that the top quark resulting from the resonance decay is polarized, and that this polarization is positive. The value of  $\mathcal{L}_{\min}$  can in fact be computed for other models with different values of the couplings  $v_t$  and  $a_t$ , hence different values of the polarization  $S$ . Figure 5.24 shows  $\mathcal{L}_{\min}$  as a function of  $S$ , for both positive and negative polarizations.

### 5.3.9 Summary

Various models predict the existence of heavy resonances, with masses of order 1 TeV, decaying into top pairs. If these resonances are produced via the strong interaction, the signal can be extracted from the expected irreducible Standard Model background. If such a signal is observed at the LHC, the top polarization



**Figure 5.24:** Minimum luminosity required to prove that top quarks are polarized, as a function of the expected polarization.

can be measured using the lepton distribution of semileptonic top decays in the top rest frame. This polarization can be used for model discrimination.

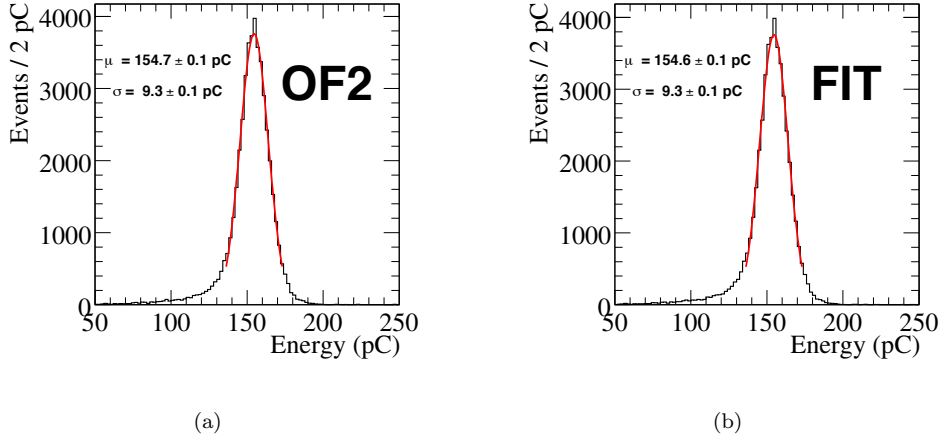
## Chapter 6

# Resumen y resultados

El LHC se ha diseñado con el principal objetivo de investigar nueva física a la escala del TeV y con la esperanza de descubrir el origen de la masa de las partículas. ATLAS es uno de los dos detectores de propósito general diseñado para estudiar los productos de las colisiones protón-protón, a energía en centro de masas de 14 TeV, que tendrán lugar en el LHC.

En esta tesis se ha estudiado e implementado en los RODs de TileCal un algoritmo de reconstrucción de pulsos digitalizados, *Optimal Filtering*. Este algoritmo proporciona la energía depositada por las partículas que atraviesan el calorímetro hadrónico de tejas de ATLAS y el tiempo de llegada de este pulso a través de la suma promediada de las muestras del pulso generado en el calorímetro.

*Optimal Filtering* ha sido implementado en los procesadores digitales de las tarjetas ROD de TileCal. Se ha estudiado la precisión necesaria de los pesos de *Optimal Filtering* y se ha elegido un formato de empaquetado adecuado para su uso en los procesadores de señal digital de los RODs. Para poder reconstruir con precisión la energía depositada por muones cósmicos durante la puesta en funcionamiento de TileCal se ha desarrollado un proceso iterativo que permite corregir la falta de sincronización entre la llegada de los datos y la digitalización de



**Figure 6.1:** Histogramas de la energía depositada por piones a 180 GeV incidiendo en un módulo de TileCal a  $\eta = 0.35$ , los datos corresponden al periodo de pruebas con haz de Julio de 2003, (a) reconstrucción con el algoritmo *Optimal Filtering* y (b) reconstrucción con el método de FIT. Se ha aplicado un ajuste Gausiano para obtener la media y la sigma de ambas distribuciones.

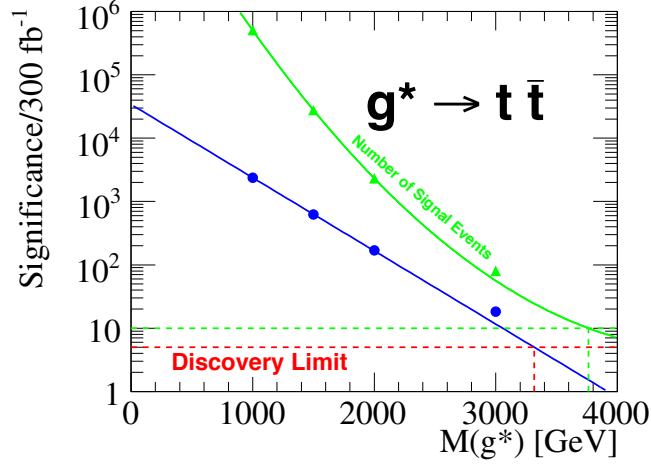
la señal. Este proceso iterativo ha sido primero validado en procesadores estándar de coma flotante con datos obtenidos a partir de haces de calibración durante el 2003 y después en los procesadores digitales del ROD, reconstruyendo en tiempo real los datos de la puesta en funcionamiento (*i.e.* muones cósmicos) durante los años 2006 y 2007.

Después de comparar la reconstrucción proporcionada por *Optimal Filtering* y la proporcionada por el método de FIT podemos concluir que *Optimal Filtering* además de ser un algoritmo más sencillo de aplicar, lo que facilita su implementación en los DSPs de los RODs, proporciona una reconstrucción de calidad compatible con la de FIT (ver Figure 6.1).

Los RODs de TileCal proporcionan las variables reconstruidas con el algoritmo *Optimal Filtering*, energía y tiempo de llegada, y un factor de calidad de la reconstrucción al segundo nivel de selección de datos de ATLAS. En este trabajo también se ha presentado la propuesta del formato de datos, compatible con el formato estándar para los eventos de ATLAS, que contiene las variables reconstruidas en los RODs. Este nuevo formato ha sido implementado en los RODs de TileCal y su correspondiente decodificador añadido al software general de ATLAS (Athena).

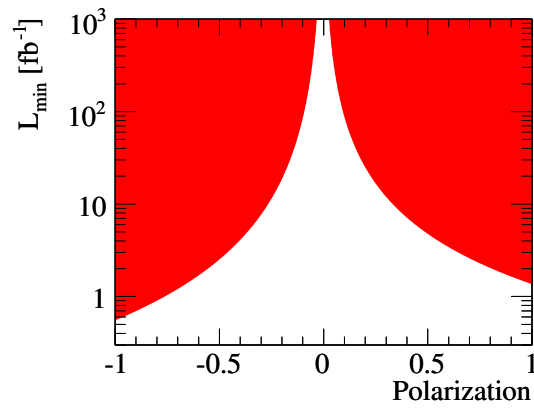
La segunda parte de la tesis estudia la sensibilidad de ATLAS a detectar evidencias de la existencia de dimensiones espaciales adicionales. Algunos modelos con dimensiones espaciales adicionales (o dimensiones extras) predicen la aparición de resonancias tipo Kaluza-Klein (KK) de los bosones *gauge*. Este es el caso del modelo estudiado en este trabajo. Este modelo, llamado aquí  $\text{TeV}^{-1}$  ED, es una variación del modelo ADD [83] con los fermiones confinados en una D-brana pero con la diferencia de que los bosones *gauge* se puede propagar en todo el espacio (*bulk*). En este trabajo se ha estudiado el potencial de ATLAS para observar las excitaciones KK del gluón a través de sus desintegraciones hadrónicas a quarks pesados. Las desintegraciones  $g^* \rightarrow b\bar{b}$  y  $g^* \rightarrow t\bar{t}$  se han investigado usando el programa de simulación ATLFAST para masas del  $g^*$  entre 1 y 3 TeV. El análisis de señales esperadas y ruidos de fondo de las desintegraciones a quarks-b muestra que esta señal es difícil de detectar, sin embargo las desintegraciones a quarks-t pueden producir una señal importante para masas del  $g^*$  por debajo de los 3.3 TeV (ver Figure 6.2). Esta señal se puede usar para confirmar la presencia del  $g^*$ , en el caso de que se observe un exceso de eventos en la sección eficaz a di-jets propuesto en [79].

Además del modelo  $\text{TeV}^{-1}$  ED existen otros modelos que predicen una resonancia del gluon similar, como por ejemplo el reciente modelo Randall-Sundrum [81,82] (RS) que incorpora una sola dimensión adicional combada. En estos casos es útil estudiar otras propiedades del proceso, además de las distribuciones de masa invariante. En este trabajo hemos usado la polarización del top que proviene de la desintegración del  $g^*$  para discernir entre varios modelos. Para  $g^*$  con masas del orden del 1 TeV desintegrándose a quarks-t, si estas resonancias se producen

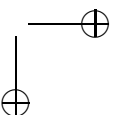
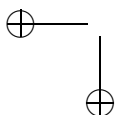
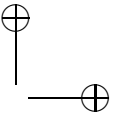
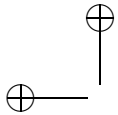


**Figure 6.2:** Significancia en función de la masa del  $g^*$  para  $g^* \rightarrow t\bar{t}$  para una luminosidad de  $\mathcal{L} = 3 \times 10^5 \text{ pb}^{-1}$ . Se ha ajustado una curva exponencial a los valores obtenidos.

a través de la interacción fuerte, la señal puede ser extraída del fondo irreducible esperado por el modelo estándar. Si esta señal es observada en el LHC, la polarización del top puede ser medida usando la distribución del lepton de las desintegraciones semi-leptónicas del top en el sistema en reposo del top (ver Figure 6.3). Esta medida se puede usar para discriminar entre varios modelos que predicen una resonancia del gluón similar.



**Figure 6.3:** Luminosidad mínima requerida para probar que el quark top está polarizado en función de la polarización esperada.





## Chapter 7

# Conclusions

The main motivation of the LHC project is to investigate the new physics at the TeV scale and to discover the origin of the mass. ATLAS is one of the two general purpose detectors designed to study the products of the proton-proton collisions at 14 TeV -center of mass energy-, that takes place at the LHC.

In this thesis it is presented the study of a digital signal reconstruction algorithm called Optimal Filtering. This algorithm provides both the energy deposited by the particles that cross the ATLAS hadronic tile calorimeter and the arrival time of the signal, by means of a weighted sum of the digital samples of the signal generated in the calorimeter.

Optimal Filtering has been implemented in the digital signal processors of the TileCal RODs and the Optimal Filtering weights have been encoded in the appropriate format to be used in the RODs. During commissioning and test beam periods the arrival of the calibration particles was not synchronized with the digitization clock. In order to properly reconstruct the energy deposited by those particles I have proposed and implemented an iterative procedure that corrects this lack of synchronization. This iterative procedure has been validated first using floating point processors with test beam data taken during 2003 and second

using the online digital signal processors of the RODs reconstructing cosmic muons from commissioning phase during 2006 and 2007.

Comparisons between Optimal Filtering and FIT method have been presented here and showed that both algorithms can achieve similar energy resolution. However Optimal Filtering is a more appropriate algorithm to run online in the ROD DSPs because it is mathematically simpler to apply.

The reconstruction routine in the ROD DSPs provides the energy and the arrival time of the signal, reconstructed with Optimal Filtering, with a quality factor of the reconstruction. This information is sent to the ATLAS second level trigger. In this work an output data format for these parameters has been proposed following the specification of the general ATLAS raw event data format. This new format has been implemented in the ROD DSPs and its decoder added to the ATLAS general software (Athena).

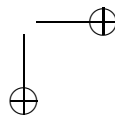
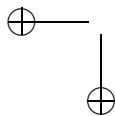
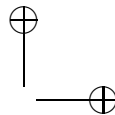
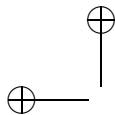
The second part of the thesis is about the ATLAS sensitivity to detect extra dimension evidences. Some extra dimension models predict the existence of Kaluza-Klein resonances of the gauge bosons. This is the case of the model studied here. This model, called here  $\text{TeV}^{-1}$  ED, is a variation of the ADD model with fermions confined to a D-brane but with the difference that the gauge bosons can propagate into the bulk. In this work I have studied the ATLAS potential to discover the KK excitations of the gluon through its hadronic decays to heavy quarks. The decays  $g^* \rightarrow b\bar{b}$  and  $g^* \rightarrow t\bar{t}$  have been investigated using the ATLF-FAST program for masses of the  $g^*$  between 1 and 3 TeV. The analysis of the expected signals and backgrounds from the excited gluon decay to b-quarks shows that the signal is difficult to detect. However, the decay to t-quarks can produce an important signal for  $g^*$  masses below the 3.3 TeV. This signal can be used to confirm the presence of the  $g^*$ , if an excess of events is observed in the di-jet cross section as proposed in [79].

The gluon resonance is predicted by the  $\text{TeV}^{-1}$  ED model, however there are other models that predict a similar resonance of the gluon, like the Randall-

## Conclusions

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Sundrum, with a single warped extra dimension. In this case it is useful to study other properties of the process, apart from the invariant mass distributions. In this work I have used the top polarization in the decays of  $g^*$  to tops to discriminate within the various models. For a  $g^*$  with mass of the order of 1 TeV decaying into top pairs, if these resonances are produced via the strong interaction, the signal can be extracted from the expected irreducible Standard Model background. If such a signal is observed at the LHC, the top polarization can be measured using the lepton distribution of semileptonic top decays in the top rest frame. This polarization can be used for model discrimination.



## Appendix A

# Glossary

**ADC** Abbreviation for analog-to-digital converter.

**ALICE** A Large Ion Collider Experiment, it is designed to study Pb Pb collisions in the LHC.

**ALU** Abbreviation for arithmetic logic unit.

**ASIC** Abbreviation for application-specific integrated circuit.

**ATLAS** A Toroidal LHC Apparatus, it is one of the five main experiments around the LHC designed to exploit the physics potential discovery of this collider.

**ATLFAST** The ATLAS fast simulation code, used in this thesis to simulate the ATLAS sensitivity to signals beyond the Standard Model.

**BC** Abbreviation for ATLAS bunch clock.

**CERN** Formerly “Conseil Européen pour la Recherche Nucléaire” commonly referred as to the European laboratory for particle physics, site of LHC and LEP colliders.

**CMS** Compact Muon Solenoid, like ATLAS, CMS is one of the five main experiments around the LHC designed to exploit the physics potential discovery of this collider.

**CPU** Central Processing Unit, it is the component in a digital computer capable of executing a program.

**CSC** The ATLAS Cathode Strip Chambers, part of the ATLAS Muon Spectrometer.

**CTP** The ATLAS Central Trigger Processor.

**DAQ** The ATLAS Central Data Acquisition system.

**DMA** Abbreviation for direct memory access.

**DSP** Abbreviation for digital signal processor.

**ECR** Abbreviation for ATLAS event counter reset.

**ED** Abbreviation for Extra Dimensions, the model that explains the hierarchy problem by means of the space geometry.

**EDMA** Refers to the external DMA of the ROD DSPs.

**EF** The ATLAS Event Filter, it is the third level of trigger acting on the full event and taking the final decision before data storage.

**EM** Abbreviation for electromagnetic.

**EMIFA** It is the 64-bit external memory interface bus A in the ROD DSPs.

$E_T^{\text{miss}}$  refers to the missing energy transverse to the beam axis.

**EW** Electroweak, the theory of electromagnetic and weak interactions.

**FF** Flat filtering algorithm, it is an energy reconstruction algorithm widely used during the TileCal testbeam period previously to the development of the FIT method, it consists on the maximal of the plain sum of five consecutive samples.

**FIT** The Fit method is an energy reconstruction algorithm based on the minimization of the  $\chi^2$ . This  $\chi^2$  evaluates the difference between the digital samples of the pulse and a parametrization of the theoretical pulse shape form.

**FPGA** Abbreviation for field programmable gate arrays.

**HAD** Abbreviation for hadronic.

**HLT** The ATLAS High Level Trigger, it is the system composed by the LVL2 and the EF.

**HPI** It is the host port interface in the ROD DSPs. A host processor can access the ROD DSPs memory space through this port.

**HV** Abbreviation for high voltage.

**ITC** The ATLAS Intermediate Tile Calorimeter, it is a stepped calorimeter structure placed in part of the gap between the TileCal barrels.

**KK** Abbreviation for Kaluza-Klein.

**L1** Refers to the level-one cache memory in the ROD DSPs of size 32 kB.

**L2** Refers to the level-two cache memory in the ROD DSPs of size 1024 kB.

**L1A** The ATLAS Level 1 Accept trigger signal, it is generated when the LVL1 trigger has been fulfilled.

**L1D** Refers to the ROD DSP L1 space for data (16 kB).

**L1P** Refers to the ROD DSP L1 space for program (16 kB).

**LAr** Abbreviation for liquid Argon.

**LEP** The Large Electron Positron collider, a collider placed in a 27 km long tunnel at CERN; to date, LEP is the second most powerful accelerator of elementary particles ever built.

**LH** Abbreviation for Little Higgs model.

**LHC** The Large Hadron Collider, a proton proton collider placed in the LEP tunnel. It is designed to be the world’s largest and highest energy particle accelerator.

**LHCb** Large Hadron Collider Beauty, it is one of the five main experiments around the LHC designed to investigate B-physics.

**LO** Abbreviation for leading order.

**LSB** Abbreviation for least significant bit.

**LSP** The Lightest Supersymmetric Particle, the generic name given to the lightest of the additional hypothetical particles found in supersymmetric models.

**LTP** The ATLAS Local Trigger Processor module. It is a 6U VME module working as interface between the TTCvi module and the CTP.

**LVDS** Abbreviation for low voltage differential signaling.

**LVL1** The ATLAS First Level Trigger, it has dedicated processors acting on data with reduced granularity from calorimeters and the muon spectrometer.

**LVL2** The ATLAS Second Level Trigger, it uses the full granularity from most ATLAS detectors, but acts only on a reduced region selected by the LVL1.

**MAC** Abbreviation for multiply-accumulative instructions.

**MC** Abbreviation for Monte Carlo.

**McBSP<sub>*i*</sub>** It is the serial port *i* in the ROD DSPs.

**MDT** The ATLAS Monitored Drift Tube chambers, part of the ATLAS Muon Spectrometer.

**MSB** Abbreviation for most significant bit.

**MSSM** Abbreviation for Minimal Supersymmetric extension of the SM.

**OC** TileCal ROD Output Controller FPGA.

**OF** Optimal Filtering, it is the energy reconstruction algorithm implemented at the TileCal ROD DSP and subject of this thesis.

**OF1** One of two approaches of the OF algorithm. This approach outputs the amplitude and timing of a PMT signal by means of a weighted sum of the digital samples. The first sample is defined as the pedestal and it is subtracted from the other samples.

**OF2** One of the two approaches of the OF algorithm. This approach outputs three parameters: amplitude, time and pedestal and then no further pedestal treatment is needed.



**OMB** The TileCal Optical Multiplexer Board, it is a 9U VME board that receives redundancy fibers from the TileCal front-end electronics, implements a CRC check and sends only the selected fibers.

**ORX** Abbreviation for optical receivers.

**PLL** Abbreviation for phase-locked-loop.

**PMT** Abbreviation for a photomultiplier tube.

$p_T$  refers to the momentum tranverse to the beam axis.

**PU** The TileCal ROD processing unit, it is a mezzanine card plugged into the ROD motherboard that implements the online reconstruction algorithms.

**QCD** Quantum ChromoDynamics, the theory of the strong interaction or color force.

**QED** Quantum ElectroDynamics, the theory of the electromagnetic interaction.

**ROB** The ATLAS Read Out Buffer, the ROB system receives process data from the RODs and sends it by request to the LVL2.

**ROD** The ATLAS Read Out Driver, a 9U VME card designed to read out the data of the ATLAS Tile Calorimeter and process all information. It is the card where the OF algorithm is implemented.

**RoI** The ATLAS Regions of Interest. This regions contain potentially interesting signals.

**ROS** The ATLAS Read Out System, it is the system composed by several ROB.

**RPC** The ATLAS Resistive Plate Chambers, part of the ATLAS Muon Spectrometer.

**RS** Abbreviation for Randall-Sundrum.

**SCT** The ATLAS SemiConductor Tracker, part of the ATLAS Inner Detector.

**SM** The Standard Model of particle physics. A theory that describes three of the four known fundamental interactions between the elementary particles that make up all matter. It is a quantum field theory developed between 1970 and 1973 which is consistent with both quantum mechanics and special relativity.

**SMD** Abbreviation for surface mounted device.

**SPS** Super-Proton Synchrotron, proton anti-proton collider at CERN, its beams provided the data for the UA1 and UA2 experiments, which resulted in the discovery of the W and Z bosons.

**SUSY** Supersymmetry is a symmetry that interchanges bosons and fermions.

**TBM** The ATLAS Trigger and Busy Module, it is a 9U VME board that receives the TTC information and distributes it through a P3 custom backplane.

**TGC** The ATLAS Thin Gap Chambers, part of the ATLAS Muon Spectrometer.

**TileCal** The ATLAS Hadronic Tile Calorimeter.

**TileDMU** Abbreviation for Tile Calorimeter Data Management Unit.

**TM** The TileCal Transition Module, it is a 9U VME board that receives processed data from the RODs and sends it to the ROS via optical fibers.

**TOTEM** Total Cross Section, Elastic Scattering and Diffraction Dissociation, it is one of the five main experiments around the LHC designed to investigate the total proton-proton cross section at the LHC.

**TRT** The ATLAS Transition Radiation Tracker, part of the ATLAS Inner Detector.

**TTC** Abbreviation for timing, trigger and control.

**TTCex** The ATLAS TTC laser transmitter, it is a 6U VME module that receives the TTC information from the TTCvi, encodes, multiplexes and sends the signals to the front-end electronics, to a TTCpr card and to the ROD system.

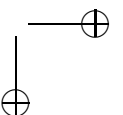
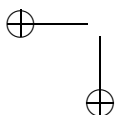
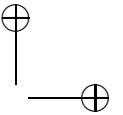
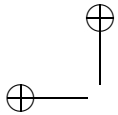
**TTCpr** The ATLAS TTC PCI Mezzanine Card receiver, it receives the TTC information.

**TTCvi** The ATLAS TTC VME interface module, it is a 6U VME module that receives the TTC information and distributes it through the A- and B-channels to the TTCex.

**UV** Abbreviation for ultraviolet.

**VME** VersaModular Eurocard. The VME bus is a computer bus standard.

**WLS** Abbreviation for wavelength shifting.



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