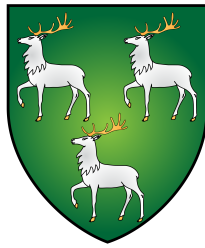


Study of CMOS prototypes for the ATLAS detector upgrade and searches for invisible decays of the Higgs boson

Luigi Vigani
Jesus College, Oxford



Thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy at the University of Oxford

Trinity Term, 2018

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Abstract

The ATLAS experiment at CERN is a large multi-purpose detector operating with outstanding performances. For its upgrade phase during the High Luminosity LHC, the tracking system will be replaced with a new system completely made of silicon detectors called ITk. Novel detectors, based on the CMOS process, have been considered for the outer layer of the ITk pixel subsystem. This thesis presents measurements obtained with prototype devices produced in the CMOS technology, and discusses the possibility of including these sensors in the ITk.

One of the biggest achievements of the ATLAS experiment is the discovery of the Higgs boson in 2012. While being a keystone for the validation of the Standard Model, the Higgs boson can also be a probe for new physics, especially by investigating its coupling to invisible particles. In this context, the $\ell\ell\nu\nu$ final state can play a major role. This thesis introduces a data-driven method for estimating the yield of the $Z + \text{jets}$ background, one of the most important background processes affecting this analysis. The results obtained with Monte Carlo events prove that the method can accurately reproduce the background yield. This is an important step to improve the evaluation of this difficult background.

Acknowledgments

It is really difficult for me to give a complete picture of what my experience has been as a DPhil student. There have been so many people and so many facts contributing to the fulfillment of my DPhil that I do not remember all of them. I hope I am not missing anyone and, if so, I hope they will forgive me.

First, I thank my supervisor, Daniela Bortoletto, for her superb job in supervising me and my work. This thesis would have never been done without her. From the first day to the last, I felt she kept an eye on me constantly, even when it was not evident, and anytime I was going off track (rather often) she was immediately there driving me to the right direction, from congratulating with me for a good intuition to scolding me when I pushed my luck too far. I believe the lessons I have learnt from her in these four years will be fundamental for my future.

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There have been then many other people from the department who have shared part of the effort to complete this work. Todd Huffmann is surely one of them: from supervising my work with the CMOS strip sensors, to giving me lots of suggestions and comments all along the DPhil, to finally reviewing my thesis and application documents. His support has been extremely valuable. I thank Jaya John, who has supported the CMOS strip project too, and has always been available for any kind of help. I thank all the people from the mechanical workshop, the IT service and the central electronic group, who have helped me when I was not so good in solving technical problems by myself.

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Chapter 1

Introduction

During the 20th century and the beginning of the 21st century, particle physics has been one of the fastest growing fields of science, with many discoveries and achievements obtained thanks to the constant effort of several scientists. Only a century occurred from the discovery of the nucleus by Rutherford to the discovery of the Higgs boson, and all the knowledge achieved in this period of time has been consolidated in the Standard Model of particle physics. This model defines the fundamental particles that constitutes the universe and their interactions. In this context, the Higgs boson represents the keystone of the whole model. The discovery of this particle was made possible by the experiments that took place at the Large Hadron Collider (LHC) at CERN, in Geneva. This thesis is based on the work performed in the framework of one of these experiments, the ATLAS experiment.

This chapter presents a brief summary of the Standard Model, the Large Hadron Collider and the ATLAS experiment.

1.1 The Standard Model

The Standard Model (SM) is a theory that illustrates the fundamental particles and their interactions. A comprehensive description of this model can be found in many text books [1–3].

According to this model, the matter is composed of particles called fermions, while the forces are mediated by other particles called bosons. All these particles are physical manifestations of quantum fields [4, 5] and are characterized by properties such as mass, charge, spin etc.

The fermions are spin-1/2 particles and they are divided in two groups, quarks (q) and leptons (ℓ), arranged in three generations. Each generation features two leptons and two quarks and their anti-particles, i.e. particles with the same mass and spin, but opposite charge.

The vector bosons are spin-1 particles, and they are the mediators of three of the four

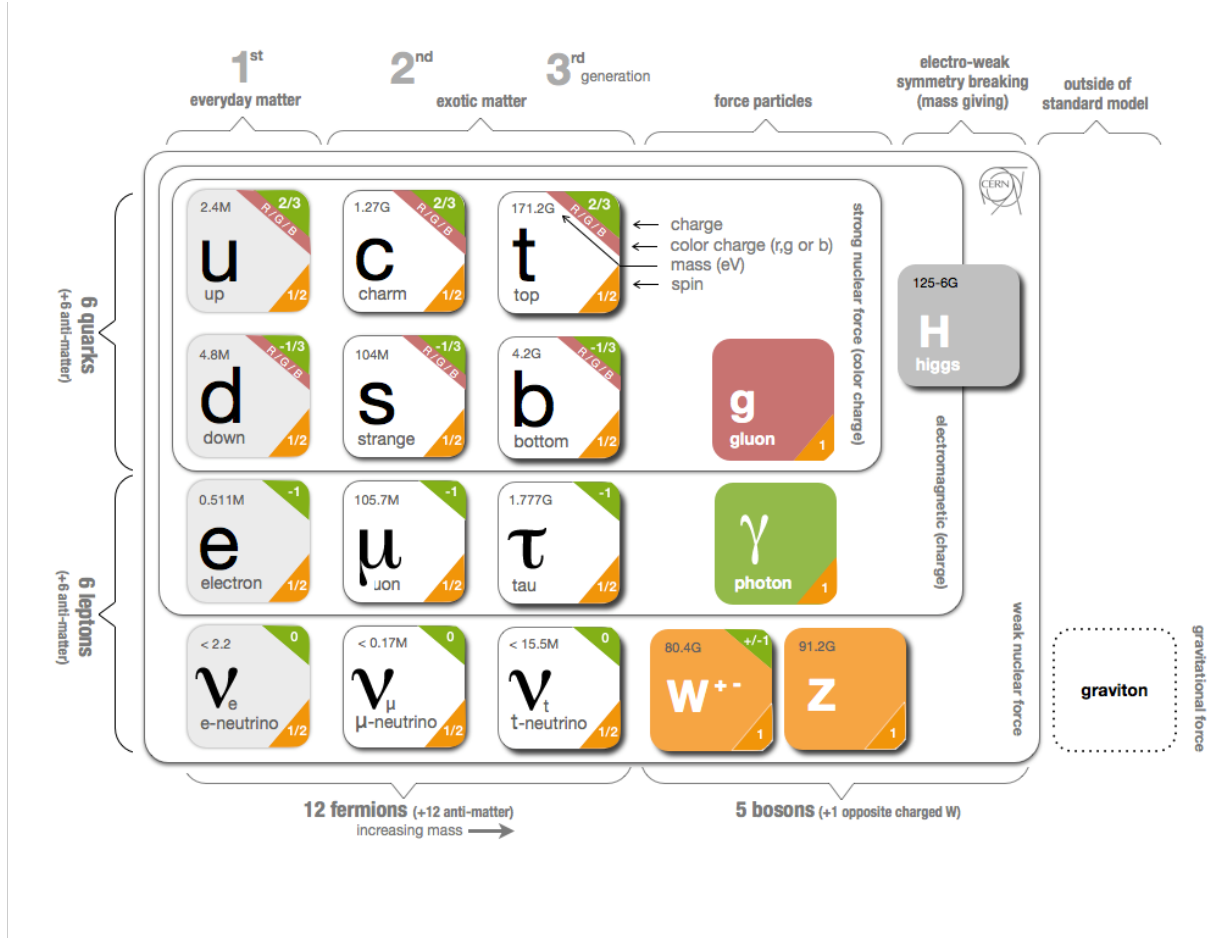


Figure 1.1: The elementary particles contained in the Standard Model and their basic properties [7].

fundamental forces, electromagnetic (EM), weak and strong. Gravity, at the moment, is not included in the Standard Model.

The strong force acts on quarks and is mediated by massless vector bosons called gluons, g , which interact with the quarks and between themselves via a special kind of charge, called colour. Because of asymptotic freedom [6], the quarks and the gluons can not stay free as singlets, but are confined into composite particles called hadrons.

The weak force is mediated by three massive bosons, the $W^\pm$ bosons and the Z^0 (or simply Z) boson. The mediator of the EM force is the photon, γ , an electrically neutral massless particle. The particles defined by the SM and their properties are shown in Figure 1.1.

The Standard Model is based on Quantum Field Theory (QFT). In this theory, the behaviour of a field is determined by the Lagrangian density (or simply Lagrangian), $\mathcal{L}$, which is a function of the fields and their derivatives. The equations of motion of the field, and consequently of the particles, are obtained by applying the principle of least action, i.e. $\delta\mathcal{S} = 0$, where $\mathcal{S} = \int \mathcal{L} d^4x$ is the integral over the space-time coordinates ($x^\mu = (x, y, z, t)$)

of the Lagrangian function [8]. According to the SM, then, the interactions among particles arise from the invariance of the Lagrangian to a local gauge transformation [9]. To preserve this invariance, then, extra terms are required, which correspond to the interactions between particles.

The three forces in the SM are generated by a local gauge symmetry which follows the $SU(3)_C \times SU(2)_L \times U(1)_Y$ algebraic group, where $SU(N)$ refers to a group of $N \times N$ unitary matrices with determinant equal to 1. In this algebraic group, the strong force is generated by the $SU(3)_C$ symmetry where C refers to the colour charge, while the electromagnetic and the weak force are unified in the $SU(2)_L \times U(1)_Y$ symmetry. Here L refers to the weak isospin coupling, which acts on left-handed particles only (particles with spin opposite to the momentum). Y , instead, refers to the weak hypercharge, which is the sum of the electric charge operator and the third component of the weak isospin.

Furthermore, one basic symmetry under which the SM is invariant is the CPT symmetry, where C stands for charge, P for parity and T for time reversal. More specifically, the CP symmetry is preserved in strong and EM interactions but violated in weak interactions. This violation of CP symmetry is at the base of the observed matter-antimatter imbalance in the universe [10–12].

The model described so far works in the case of massless bosons. The observed masses of the W and Z bosons, then, are explained by the spontaneous symmetry breaking of the $SU(2) \times U(1)$ gauge group [13–15], as will be shown in Section 5.1.1.

1.2 The Large Hadron Collider

The Large Hadron Collider (LHC) is a 27 km diameter accelerator located at CERN, near Geneva, which collides protons with protons at a centre of mass energy, $\sqrt{s}$, of 13 TeV (6.5 TeV per proton beam) [16]. The beams consist of short-pulse bunches which contain $\sim 10^{11}$ protons. The protons in the bunches are obtained by stripping the outer electron of hydrogen atoms in a duoplasmatron source.

The protons are accelerated in several machines, where every machine increases the speed of the protons and injects in the next one (see Figure 1.2). The first step consists of a linear accelerator, the Linac, which accelerates the protons up to 50 MeV. The second step is the booster ring, where the proton beams are accelerated to an energy of 1.4 GeV. Then, in the third step, the protons move to the Proton Synchrotron (PS), where the energy is increased to 26 GeV. After the PS, the protons are injected in the Super Proton Synchrotron (SPS), where they reach an energy of 450 GeV. Finally, the protons arrive to the LHC ring, where they achieve the final energy of 6.5 TeV.

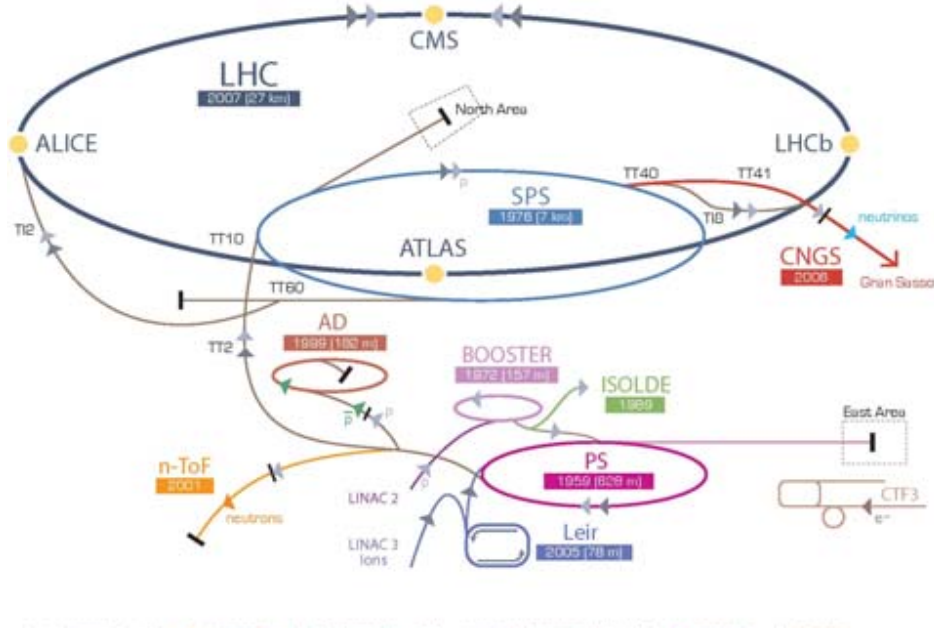


Figure 1.2: Sketch of the CERN accelerator complex with its chain of accelerators [17]. Those involved in the proton acceleration are: the linear accelerator (Linac), the Booster, the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS) and the LHC ring.

In the LHC, protons are accelerated by radio frequency superconducting cavities oscillating at a frequency of 400 MHz and bended by 1232 dipole magnets. The dipole magnets produce a field of more than 7 T by generating a current of 11.8 kA through superconducting coils. These coils are made of niobium-titanium (NbTi) and they are cooled down to 1.9 K using superfluid helium. 858 quadrupole magnets are placed along the path of the protons to focus and bunch them together. The cryogenic components of the magnets are thermally isolated by means of a high insulating vacuum ($\sim 10^{-6}$ mbar).

There are four collision points along the LHC ring, one for each of the experiments. Among these experiments, ATLAS and CMS are general purpose detectors, LHCb is specialized on events with b-hadrons (hadrons containing b quarks) and ALICE studies multi-track events produced by either heavy ion or proton collisions.

In contrast to electron-positron colliders, such as LEP, where the energy of the initial state is well known, at the LHC the initial energy of the colliding quarks and gluons can't be determined, since they carry just a fraction of the proton energy. The portion of energy carried by each quark or gluon in a hadron is described by parton distribution functions (PDFs) [18]. The impossibility to predict the total energy at each collision is a source of uncertainty in the measurements performed at the LHC.

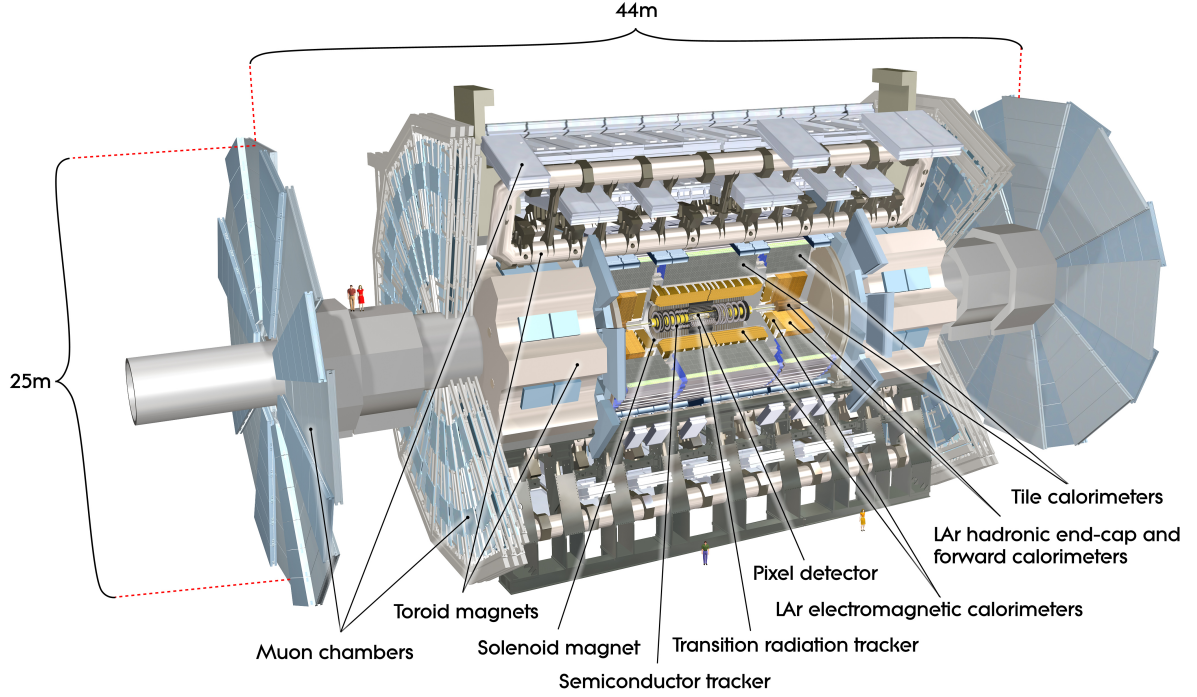


Figure 1.3: The ATLAS detector and its sub-detectors [20].

1.3 The ATLAS Experiment

ATLAS [19] is a general purpose experiment located at Point 1 of the LHC in Meyrin, Switzerland. The detector is 44 m in length, 25 m in height and 7000 tonnes in weight. It consists of sub-detectors disposed in a multi-layered cylindrical configuration for a total of 100 million read-out channels. The detector processes particle collisions at a rate of 40 MHz, which is the bunch crossing frequency of the LHC.

The purpose of such a detector is to reconstruct with high accuracy the position, momentum and energy of charged and neutral particles emerging from the interaction point. The final goal is to study the properties of high energy physics processes. The angular coverage of the detector is close to 4π .

The ATLAS experiment is conceived to verify the SM predictions to very high precision, as well as to search for new physics phenomena, which would manifest as excess number of events in data over the SM background expectation. A schematic view of the ATLAS detector can be seen in Figure 1.3.

The sub-detectors of ATLAS are grouped in four detector subsystems: the inner detector (ID), the EM calorimeters, the hadronic calorimeter and the muon spectrometer (MS). In this chapter, after a description of the coordinate system, the sub-detectors will be described in detail, along with a discussion of the trigger.

In order to bend the charged particles, ATLAS uses two separate magnetic systems. The

first is a superconducting solenoid coil, which generates a solenoidal field of 2T in the ID and the second is a toroidal field in the muon systems, generated by three toroidal magnets [21].

1.3.1 The coordinate system

ATLAS data reconstruction is based on a right-handed coordinate system whose origin is at the centre of the detector. The z axis is parallel to the beam line, the y axis points upwards from the beam pipe and the x axis points horizontally towards the centre of the LHC ring. Given the circular symmetry, on the plane transverse to the beam line it is more practical to use circular coordinates, with r (radius) and ϕ (azimuthal angle) instead of x and y . Furthermore, an additional coordinate is used to denote the angle of a particle relative to the beam axis. In this case there is a complication though, as the parallel component to the beam axis (z coordinate) of the total momentum is non-zero, because the interacting partons do not have the same energy. The particle emerging from the interaction vertex, therefore, can be boosted along the z axis. In this case, using the polar angle, θ , of a spherical coordinate system does not take into account the relativistic effect of the contraction of distances, and its value is not Lorentz-invariant. To overcome this problem, another variable is used instead of θ , i.e. the pseudorapidity, η . This is defined as a function of the polar angle, θ as:

$$\eta = -\ln(\tan(\theta/2)) \quad , \quad (1.1)$$

where polar angle is defined from the z axis, with positive and negative z corresponding to $\theta = 0$ and π respectively.

Since the sum of the momenta is zero in the transverse ($r - \phi$) plane, it is convenient to define the variables according to the transverse components, i.e. their projections on that plane. The transverse component of the particle momentum and energy are then defined as p_T and E_T . Another variable commonly used in many studies is the angular separation between particles, defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Furthermore, the detector is divided into three regions: the central (barrel) region and two forward (end-cap) regions. The central region extends from $\eta = 0$ to $|\eta| = 2.4$, while the forward regions extend between $\eta = \pm 2.4$ and $\eta = \pm 4.9$.

1.3.2 The Inner Detector

The ID is a highly accurate tracking and vertexing system placed very close to the interaction point inside the ATLAS experiment. Nearly all charged particles emerging from the

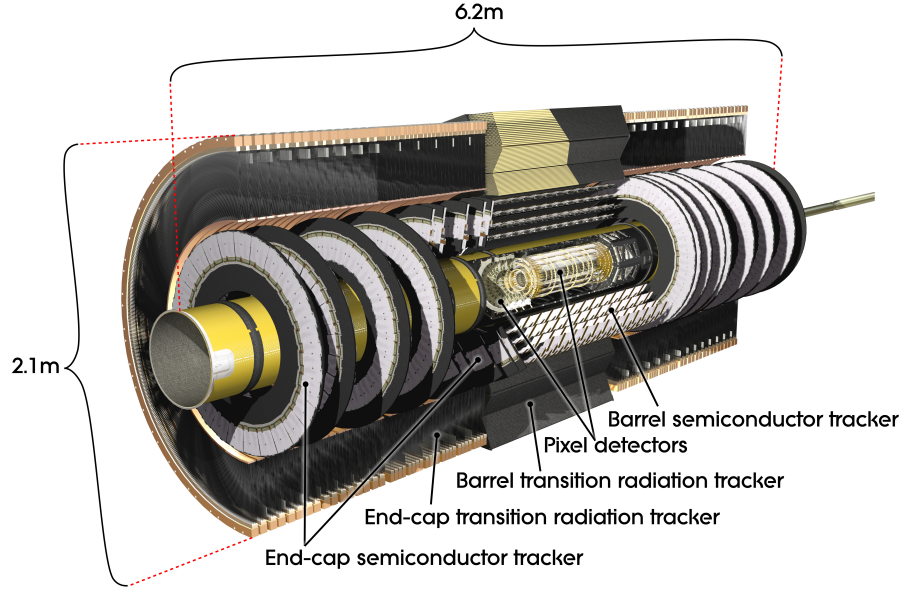


Figure 1.4: Section view of the ATLAS inner detector used in Run-1 [19].

interaction point will be detected and their tracks reconstructed by the ID. This task is very important as it is essential to measure both the position of the particle and the track curvature, which determines its charge and momentum.

The ID consists of three sub-systems: the silicon pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT). A section schematic of the ID can be seen in Figure 1.4.

The silicon pixel detector [22] is built with 1744 silicon pixel sensors. Each sensor has a size of $19 \times 63 \text{ mm}^2$, is $250 \text{ }\mu\text{m}$ thick and contains 47268 pixels. About 90% of pixels have a pitch of $50 \times 400 \text{ }\mu\text{m}^2$, while the remaining have a larger pitch of $50 \times 600 \text{ }\mu\text{m}^2$. The total amount of read-out channels is 80 million.

The principle of operation of silicon detectors will be explained in detail in the next chapter.

During the long shutdown of the LHC between 2012 and 2015, an extra layer of silicon pixel sensors was added to the ID between the beam pipe and the innermost pixel (B-) layer. This new layer is called the insertable (B-) layer, or IBL [23]. It consists of 14 staves arranged in a cylindrical configuration around the beam pipe, with an average distance between the sensors and beam pipe of 33 mm. Each staff has a size of $64 \times 2 \text{ cm}^2$ and contains 32 individual chips, each of them containing 26880 pixels. A schematic view of the IBL, along with the rest of the ID, can be found in Figure 1.5.

The SCT is placed around the pixel detector and consists of 4088 modules of silicon strips,

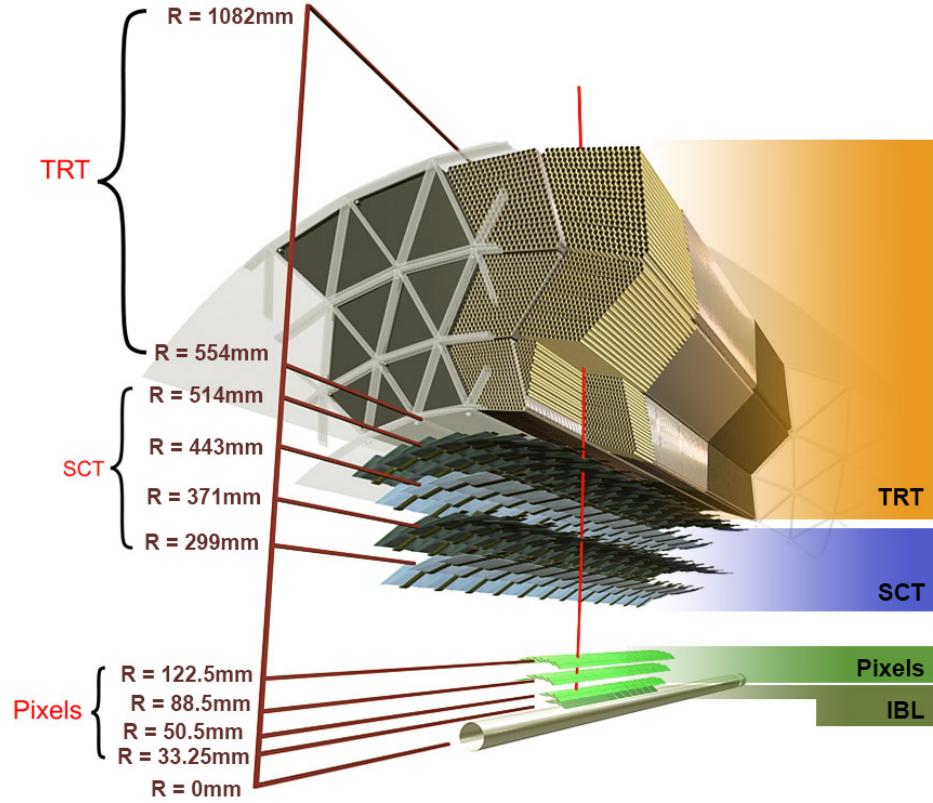


Figure 1.5: Schematic view of the ATLAS Inner Detector with its sub-systems: the Insertable B-layer (IBL), the pixel detector, the semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT) [24].

for a total of ~ 6.3 million read-out channels. It is divided into four concentric barrel layers and two end-cap regions. The strips are $80 \mu\text{m}$ wide and $\sim 12 \text{ cm}$ long in both endcaps and barrels. The strip modules are made of back-to-back layers of strips, rotated with a stereo angle of 40 mrad with respect to each other to provide tracking information in the longitudinal (beam) direction.

The TRT is made of straw drift tubes. These detectors can both reconstruct the charged particle tracks and discriminate between different particle types [25]. The principle of operation of the TRT is that transition photons are produced when charged particles pass through media with two different dielectric constants. In the TRT, the straw tubes are filled with a mixture of $\text{Xe}/\text{CF}_4/\text{CO}_2$ gases, which have a high absorption rate of the transition photons. The TRT system is divided into three regions, one barrel region and two endcap regions. The barrel region ($|\eta| < 1.0$) consists of 52,544 144-cm-long straws placed parallel to the beam axis. Each end-cap is designed with 122,880 37-cm-long straw tubes arranged in a wheel geometry. The read-out channels are twice the number of straws, since each end of the anode wires is read out separately.

The resolution in the $(r - \phi) \times z$ coordinate is $8 \times 40 \mu\text{m}$ for IBL, $10 \times 115 \mu\text{m}$ for the rest of the pixel detector, $17 \times 570 \mu\text{m}$ for the SCT and $130 \times 130 \mu\text{m}$ for the TRT [26].

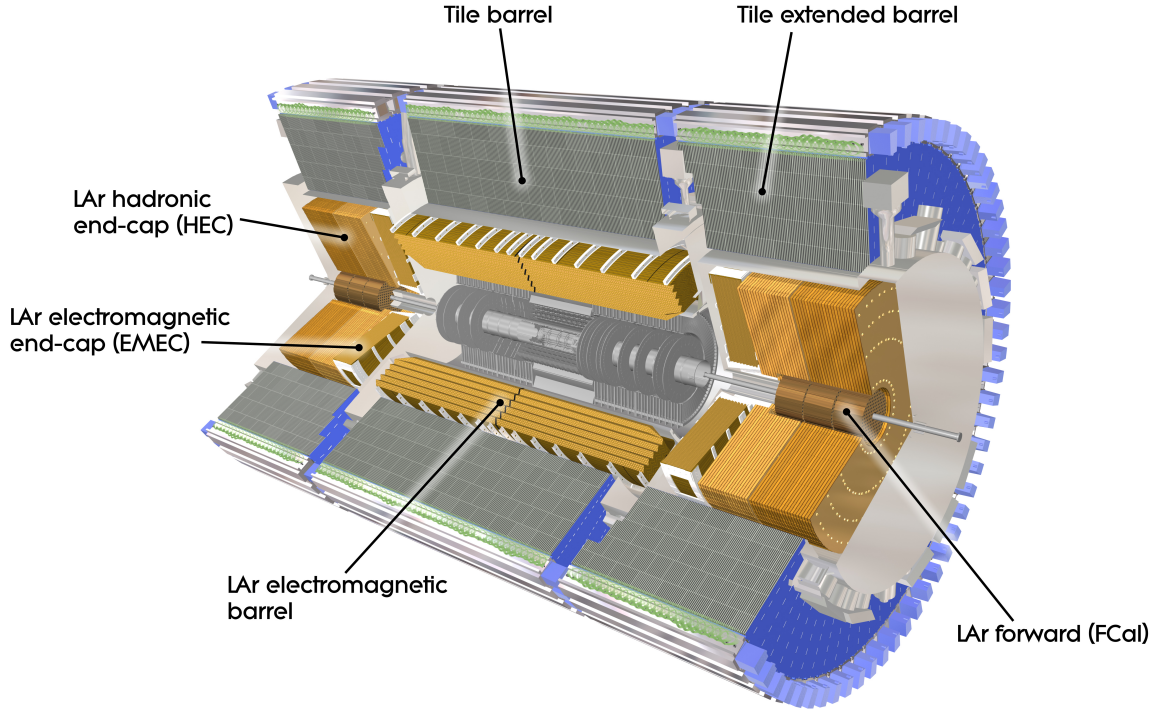


Figure 1.6: Layout and sub-detectors of the ATLAS calorimeter system [28].

1.3.3 The Calorimeters

Outside the tracking system, the calorimeter sub-systems capture and absorb a wide range of particles, in order to measure their energy (Figure 1.6).

Electrons, positrons and photons are absorbed in the EM calorimeter, containing liquid argon (LAr) [27]. Hadrons, instead, are absorbed by the tile calorimeter in the central barrel region and LAr calorimeters in the forward end-cap regions.

1.3.3.1 Electromagnetic calorimeters

In the EM calorimeter, the particle energy absorption occurs via ionisation showers. In this process, charged particles traverse the material in the calorimeters (the absorber material) and generate an electromagnetic shower through bremsstrahlung and pair production. The process happens until the particles' energy is too low. This way, by reconstructing the showers inside the calorimeter, one can compute the energy of the original parent particle, while from the shower profile one can extract additional information on the original particle type.

The LAr calorimeter is designed with interleaved absorbers made of lead and stainless steel and sub-detectors made of electrodes submerged in liquid argon, cooled to a temperature of 88 K. The absorbers' goal is to develop the electro-magnetic shower, while the sub-detectors measure the energy of the particles in the shower. When a charge particle reaches the calorimeters, it releases ion-electron pairs in the liquid argon. These pairs then drift in the electric field formed between the electrodes. The charge is then collected on the electrodes and processed by the electronics to form the signal. The released charge is proportional to the energy of the charged particles crossing the LAr [29]. Liquid argon has been chosen for many reasons, such as precise energy resolution, stability (it is a noble gas), radiation hardness and abundance.

The LAr calorimeter is divided into a central barrel chamber and two EM end-cap chambers (EMEC). The central barrel extends in the region $|\eta| < 1.475$ and is divided in two half-barrels, each with an accordion shaped geometry for a uniform coverage on ϕ . Along the radial coordinate, the central barrel is divided into three layers. The first layer is finely segmented to accurately measure the shower position, while the second and third layers are coarser, in order to collect the shower energy.

Another LAr sub-detector, the pre-sampler, is placed before the barrel, in order to measure the energy of the electrons and photons before they enter the calorimeters and therefore to estimate the energy loss in the calorimeter itself. A layout of the central barrel is shown in Figure 1.7.

The region $1.37 < |\eta| < 1.52$ features detector support structures which are not equipped for precise energy measurements, and therefore this region is typically removed from most analyses. Likewise the barrel chamber, the EMEC sub-detector is based on an accordion geometry.

The LAr resolution at the Z mass has been measured in the ee decay channel, and it has been estimated to be 1.6 ± 0.01 GeV [30].

1.3.3.2 Hadron calorimeters

The hadronic calorimeters are used to absorb and measure the energy of the hadronic objects coming out of the interaction vertices. They are divided into the tile barrel calorimeter, the hadronic end-cap calorimeter (HEC) and the forward calorimeter (FCAL).

The tile barrel calorimeter is placed around the LAr calorimeter, covering the region $|\eta| < 1.7$ [31] and it is divided into three separate cylinders, one central barrel in the region $|\eta| < 1.0$ and two barrels in the regions $0.8 < |\eta| < 1.7$.

The calorimeters feature an active component, made of plastic scintillators, to reconstruct the shower, and an absorber component, made of iron, to stop highly energetic hadrons [32]. When a particle passes through the scintillators, it releases energy through excitations in

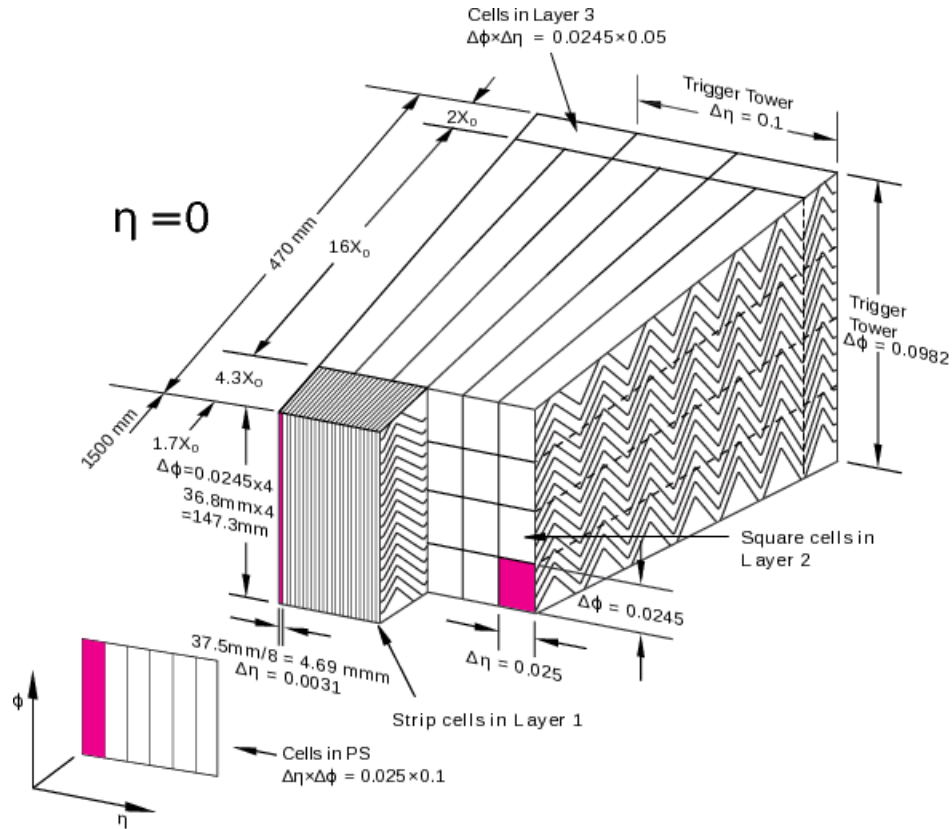


Figure 1.7: Layout of the electromagnetic barrel calorimeter and the pre-sampler with the dimensions of the calorimeter cells and trigger towers [27].

the atoms. The atoms then emit light when they de-excite. The intensity of the collected light is proportional to the energy of the particle [33].

The barrels are segmented into 64 wedges (modules) along the azimuthal direction achieving a granularity of 0.1 radians. The granularity on the polar coordinate varies from 0.1 to 0.2 radians. The tiles' granularity is coarser compared with the LAr calorimeter, since the shower profiles of the hadrons is longer than that of the photons and electrons. A schematic view of the tile calorimeter is available in Figure 1.8.

To transmit the light collected by the scintillators, wavelength shifting fibres are connected to photomultiplier tubes where the signal is converted and amplified.

The HEC is placed beyond the barrel in the regions $1.5 < |\eta| < 3.2$, and it consists of two wheels on each side of the barrel chamber. Each wheel is made of flat parallel copper plates, which act as the shower absorber material, while the active material is liquid argon.

The FCAL [34] is located in the regions $3.1 < |\eta| < 4.9$. It consists of three modules constructed of electrode rods parallel to the beam pipe, sitting in a metal matrix absorber. The first plate is made of copper and used mostly for electro-magnetic measurements. The other two, instead, are made of tungsten and are used for the reconstruction of the hadronic activity.

The resolution depends on the energy, and it tends to 3% for highly energetic hadrons [35].

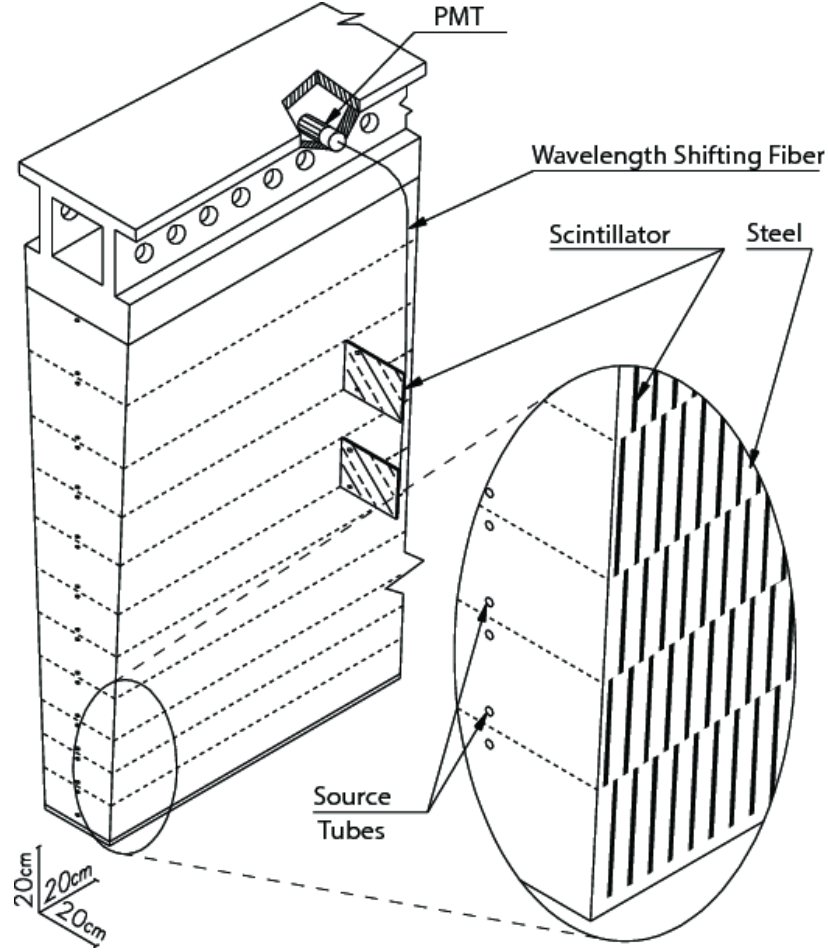


Figure 1.8: The layout of the tile barrel calorimeter, including its alternating steel and scintillator structure and the light detection system [31]. In the ATLAS detector, this section would be positioned parallel to the beam line, with particles entering from the bottom of the section.

1.3.4 The Muon Spectrometer

The muon spectrometer (MS) is the outermost detector in ATLAS, dedicated to the measurement of the momentum and energy of the muons emerging from the interaction vertices (see Figure 1.9) [36]. It is divided into three sections, a barrel section ($|\eta| < 1.05$) and two endcap sections, ($1.05 < |\eta| < 2.7$). The MS consists of the monitored drift tubes (MDTs), the cathode strip chambers (CSCs), the resistive plate chambers (RPCs) and the thin gap chambers (TGCs).

The MDTs are made of a total of 1088 pressured drift tubes, with a diameter of about 30 mm, filled with Ar/CO₂ in 93%/7% proportion at 3 bars of pressure [38]. The drift tube chambers are arranged into three layers. In crossing the drift tubes, the muons release electrons through ionization, which are then collected at a central tungsten-rhenium wire operating at a 3080 V. The total area covered by the MDTs is 5500 mm².

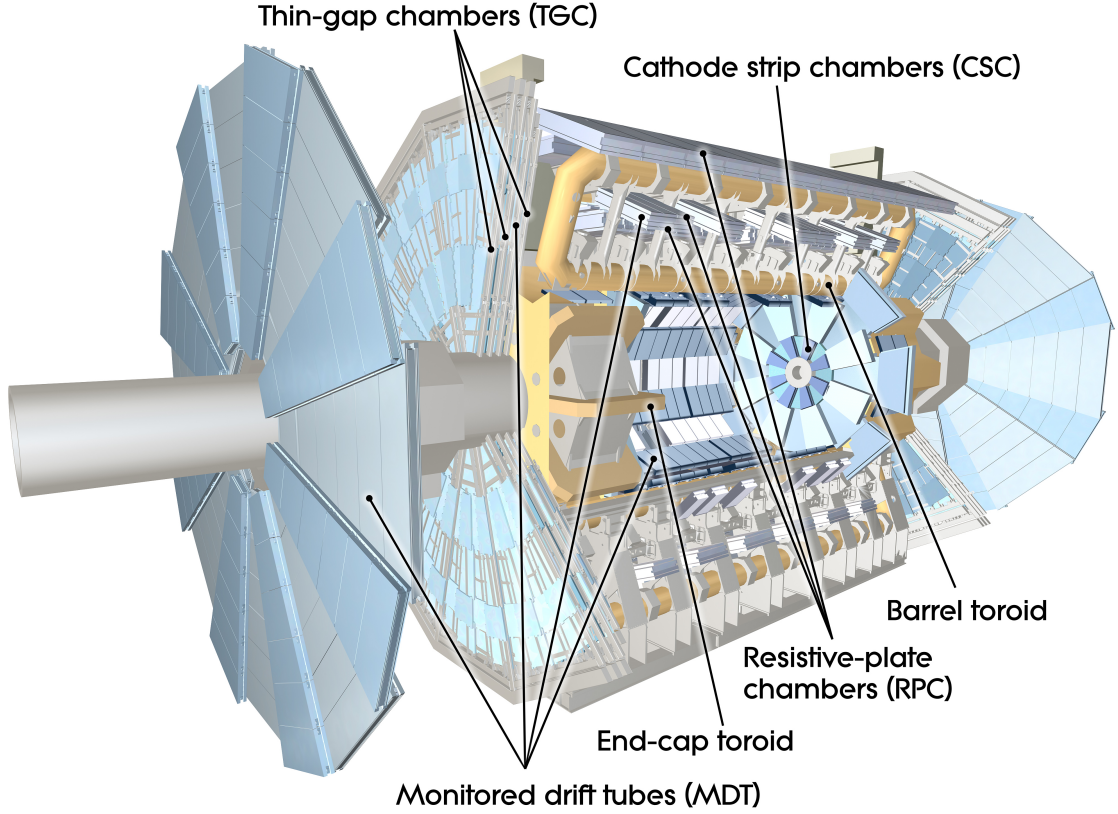


Figure 1.9: The sub-detectors of the muon spectrometer and the toroidal magnet system [37].

The CSCs are multi-wire proportional chambers (MWPCs). Since their cathodes are segmented into orthogonal strips, they can measure both spatial coordinates [39]. The CSCs are divided into two disks, each of them further segmented into eight chambers. Each chamber has four planes which provide four independent η, ϕ measurements and operate at a voltage of 1900 V and a gas mixture of Ar/CO₂ in 80%/20% proportion. Given their good performance in terms of hit rate and time resolution, the CSCs are placed in the end-cap regions ($2.0 < |\eta| < 2.7$).

The RPCs consists of three concentric cylindrical layers, placed in the region $|\eta| < 1.05$, each featuring parallel electrode plates with a gaseous mixture [40]. When a muon passes through the detector, it generates an ionisation avalanche, which is then collected at each electrode. The electric field strength is 4.9 kV/mm. The distance between the first two layers is relatively short, to allow triggering on low p_T muons ($\sim 6 - 9$ GeV), while the distance between the second and the third is larger, to allow triggering on high p_T muons ($\sim 9 - 35$ GeV).

The TGCs are made of multi-wire proportional chambers, placed in the end-cap region [41]. They cover the region $1.05 < |\eta| < 2.4$. Given their large voltage potential (2900 V) and the small wire-to-wire separation, they achieve a good time resolution. The wire width varies as

a function of η , ranging from ~ 11 mm to ~ 56 mm. A toroidal magnetic field is generated by three superconducting toroidal magnets, which produce a 0.5 T magnetic field in the barrel and a 1 T magnetic field in the endcaps. Thanks to these features, the relative resolution of the MS is 3% over a wide p_T range, with a maximum of 10% for $p_T = 10$ GeV.

1.3.5 The Trigger System

Since the collision rate is extremely high (40 MHz) and the amount of data coming out of the sub-detectors is very large, it is virtually impossible to record all the data in every single interaction. Furthermore, a great part of the events in pp collisions are low energy scatterings, which are not interesting for the physics goals of ATLAS. For these reasons, dedicated trigger systems are employed to record events which might show interesting physics [42]. Given that the total available rate of recording is 1 kHz, the portion of accepted events is of the order of 10^{-6} .

The ATLAS trigger system is divided into two general “trigger levels”: the Level-1 (L1) trigger and high level trigger (HLT). The L1 trigger is based on hardware equipment which performs quick event decisions based on calorimeter and muon trigger information. This reduces the rate down to ~ 100 kHz [43]. The HLT makes use of more accurate information from the calorimeters, ID and MS. In Run I, the HLT was based on partial event data, and event filter farms which used the full detector information. In Run II, the two triggers were combined into a single farm to reduce the complexity of the hardware and software systems and to better share the resources.

There are triggers for all reconstructed objects, like the $e^\pm, \mu^\pm, \tau^\pm$, jets and E_T^{miss} . The triggering process is performed at the L1 trigger by means of two trigger algorithms, the first using calorimeter granularity information (L1 Calo) and the second using the information from the muon spectrometer (L1 Muon). The L1 Calo trigger algorithm implements a sliding window technique [44] which cluster calorimeter cell towers in “trigger towers”, with dimensions of 0.1×0.1 in $\Delta\eta \times \Delta\phi$. The trigger towers are then used to identify maxima in the transverse energy E_T . The algorithm then defines regions of interest (RoI) around the maxima corresponding to candidate objects. The RoI is then used by the HLT for regional reconstruction in its algorithms. The RoI can vary for the different reconstructed objects, making it possible to have different triggers for different objects.

The HLT algorithm can use either the RoIs from L1 or the full detector information can be used. If the event passes the HLT, it is stored for offline reconstruction, calibration and analysis.

In addition, triggers can be un-prescaled or prescaled, where un-prescaled triggers record all events which pass the given set of triggers, while the prescaled triggers select only a fraction

of accepted events. Prescaling triggers are used in the case of high rate to ensure that the recording rate does not exceed their bandwidth limit. In this case, a scale factor must be applied during the event reconstruction.

1.4 High Luminosity LHC and Inner Tracker

In the Large Hadron Collider, the protons are being collided at an energy of 13 TeV and with a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The centre of mass energy of the machine will increase to 14 TeV for Run 3 and, later, the machine will undergo an upgrade, denoted as the High Luminosity LHC or HL-LHC, which will increase the instantaneous luminosity to about $7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [45]. The HL-LHC phase will start in 2026 and will last about 10 years. During this phase, the bunch crossing time will remain 25 ns, and to enhance the luminosity the number of proton collisions per bunch crossing will be increased from the current 23 to about 200.

In order to achieve these results, the HL-LHC will use several key innovative technologies, such as cutting-edge 11-12 Tesla superconducting magnets, compact superconducting crab cavities with ultra-precise phase control for beam rotation and loss-less superconducting links [46].

1.4.1 The Inner Tracker

Along with the LHC, the ATLAS experiment will be upgraded too, in order to cope with the new requirements set by the increase of luminosity. In particular, the higher instantaneous luminosity requires the data acquisition system to be faster and provided with more throughput, while the sensors will need to be more radiation tolerant. For instance, the silicon detectors in the tracking system will be affected by this enhancement in luminosity, as they constitute the innermost part of the experiment, i.e. the closest to the interaction point. As explained in the next chapter, the exposure to radiation can significantly degrade their performance.

The current Inner Detector, therefore, will be replaced with a new all-silicon tracker, the Inner Tracker, or ITk. This is divided into two sub-subsystems, a Pixel Detector in the innermost part and a Silicon Detector in the outermost [47, 48].

Both the Pixel Detector and the Strip Detector will be designed with a barrel region in the centre and two end-caps on the sides.

The Pixel Detector barrels will be arranged in five cylinders, from a radius of 36 mm to a radius of 274 mm. In the end-cap regions, the positions of the rings along the beam axis are

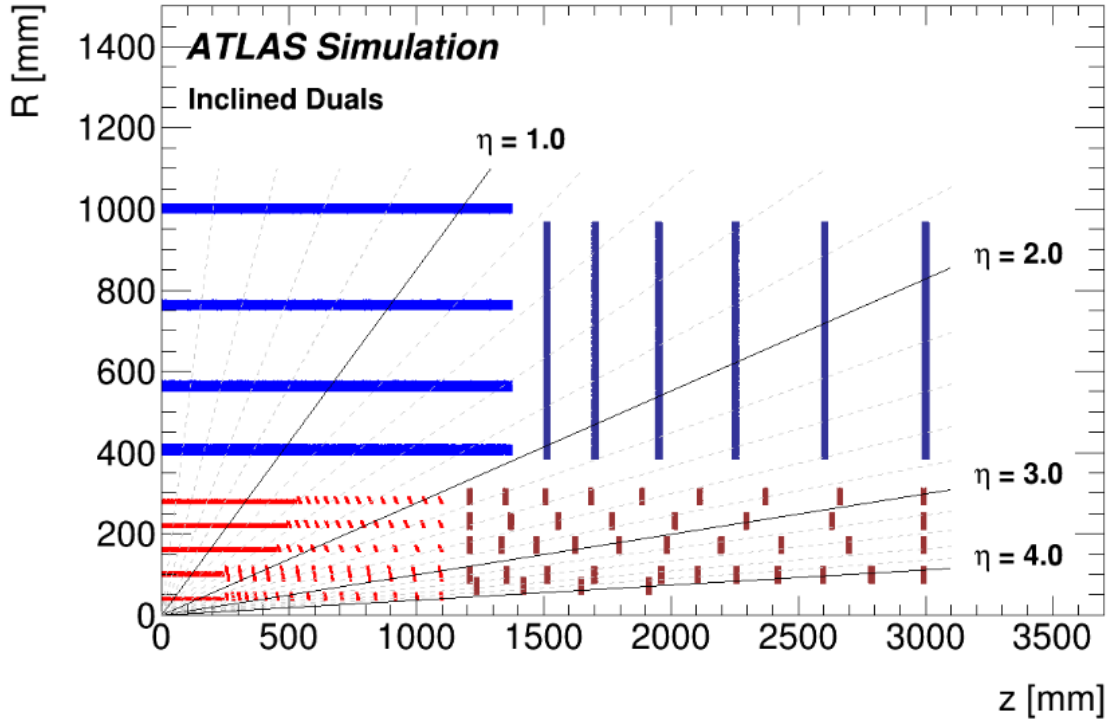


Figure 1.10: Schematic layout of one quadrant of the ITk for the HL-LHC phase of ATLAS. The Pixel Detector layers are visible in red, while the Strip Detector layers are in blue. The horizontal axis is the axis along the beam line with zero being the interaction point [47].

disposed in order to have an hermetic coverage for tracks coming from the collision region up to $\eta \sim 4$. The number of rings in the end-cap have not yet been optimised. The pixel size will be either $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$ (the two options are under consideration now), and the sensor thickness will be $100 \mu\text{m}$ for the innermost layers and $150 \mu\text{m}$ elsewhere.

The strip barrel system extends 1400 mm in the two directions along the beam axis and will be arranged in four layers disposed at radii ranging from 405 mm to 1000 mm. The strip length is 24.1 mm for the two innermost layers and 48.2 mm in the two outermost, while the pitch is $75.5 \mu\text{m}$ for all the layers. The strip sensors in the end-cap systems are grouped in disks. The strips are radially distributed and pointing to the centre of the beam axis. The strip lengths and widths are optimised to keep the strip occupancy below 1%. The strip length ranges from 19.0 mm in the region closest to the beam axis to 60.1 mm in the outermost region, while the strip width varies from $69.9 \mu\text{m}$ to $80.7 \mu\text{m}$. The tracking detector is surrounded by a polyethylene moderator to moderate neutrons from the calorimeters.

A scheme of the ITk layout is shown in Figure 1.10, while the whole detector can be visualized, in the simulation framework, in Figure 1.11.

For tracks with p_T of 100 GeV, the resolution of the ITk will be below $10 \mu\text{m}$ for $|\eta| < 3.0$. This is estimated to be 20-30% worse than the resolution in Run 2 because of digital clustering and the larger inner radius of the first pixel detector layer. Nevertheless, the momentum

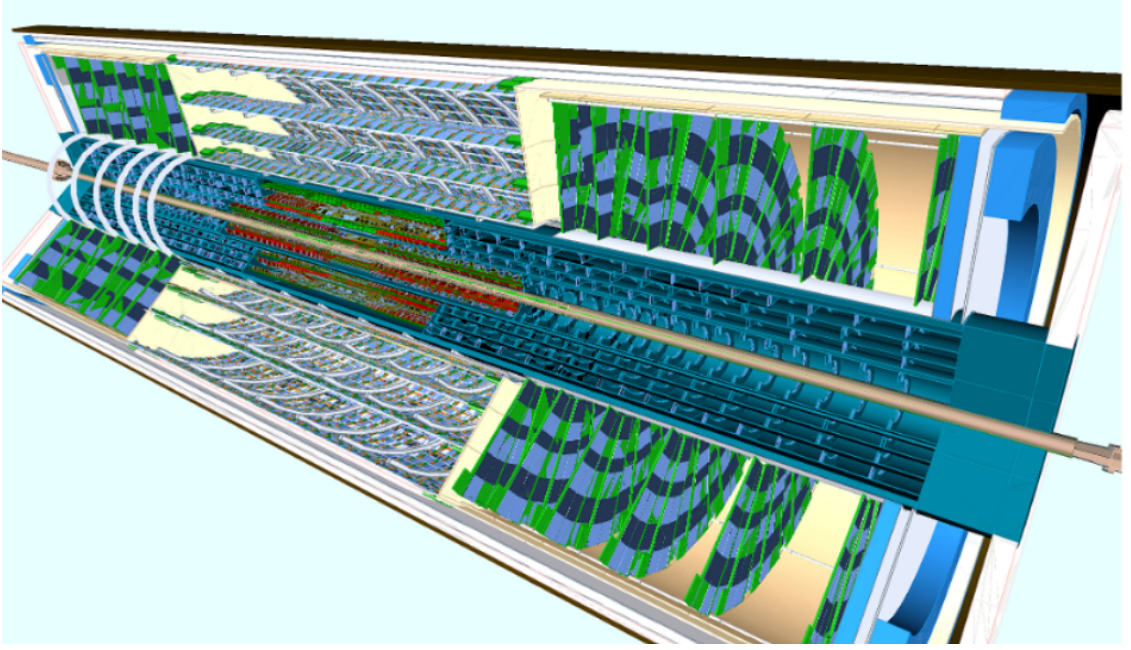


Figure 1.11: A visualization of the ITk from the simulation framework [48]

resolution is generally 50% better in the ITk than in Run 2, primarily because of the higher precision of the strip tracker compared to the TRT and of the reduced material. The resolution degrades towards the forward region, mostly due to the fact that the particles traverse less of the magnetic field generated by the solenoid.

Given the higher particle rate, the trigger system will be upgraded as well. Since the initial operation of the HL-LHC will not be at the ultimate luminosity, a similar single-level hardware trigger as the current one can be satisfactory, but the rate will increase to 1 MHz. This will be called the Level-0 trigger. However, when the full luminosity will be reached, a two hardware trigger staged system will be necessary, since the 1 MHz limit to the trigger rate may compromise the acceptance for purely hadronic final states. This new trigger will be based on a fast hardware track-finding system, which will suppress most of the backgrounds. This will be the Level-1 trigger. This way, the Level-0 trigger rate of a few MHz can be brought down to a rate below 1 MHz.

Chapter 2

Silicon Detectors and CMOS technology

In most of modern high energy physics collider experiments, silicon detectors play a crucial role in event reconstruction. Given their excellent spatial resolution, in fact, they are an ideal solution for tracking and vertexing applications. For this reason, during the high luminosity phase of LHC, the ATLAS experiment will implement a tracking system completely made of silicon detectors, the ITk (see Chapter [1.4.1](#)).

In recent decades, silicon has been proven to be an excellent material for particle detection. Nevertheless, the signal production and collection can sometimes be complicated, and therefore the process of fabricating the detector can be rather laborious. In many experiments, in fact, to make the signal strong and fast enough, high bias voltage must be applied to the silicon bulk. Thus the read-out circuitry, which works at low voltage, must be separated from the sensing part. The standard way of achieving this is to produce the sensing and the read-out components separately and merge them together in a process called hybridization. Generally this process is very expensive, thus making the employment of these devices less favourable. For this reason, other read-out solutions, based on CMOS technology, have been considered in recent years.

In this chapter the principles of silicon detectors will be outlined, starting from the fabrication process, moving then to the signal production, to the read-out, and to the usage in tracking systems. Some important features regarding their operational performances will be also discussed. In the last section, the novel implementation of the CMOS technology will be shown, along with a detailed description of the prototypes studied in this thesis. Further references for this section can be found in [\[49\]](#), [\[50\]](#) and [\[51\]](#).

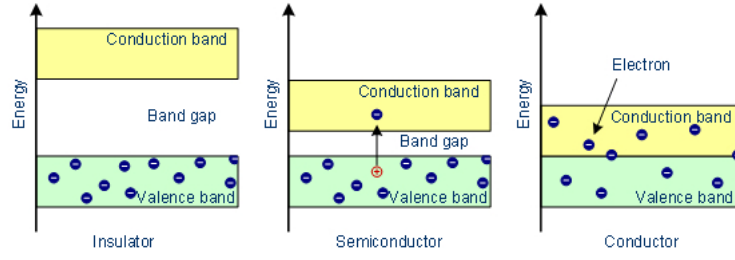


Figure 2.1: Band gap scheme of metals, semiconductors and insulators [51].

2.1 Semiconductor Physics

Depending on their conductivity, materials can be divided into three categories: metals, semiconductors and insulators. The principles of conductivity are explained by the band theory of materials. According to this theory, in a lattice of atoms electrons can have certain allowed energies. These energies group together in energy bands. The lowest atomic energies form a band called the valence band. In addition, there is a band of higher energy values called conduction band where electrons are free to move. The differences between the three categories of materials, then, lie in the band gap between the valence and the conduction bands. In metals, for instance, there is no band gap, and electrons are free to move between the two bands. In insulators, on the other hand, the band gap is larger than the energy given by thermal excitation, so the electrons can not move away from the valence band. In semiconductors, finally, the band gap is not so large, and eventually electrons can move between bands due to thermal excitation. In that case, the state from which the electron was excited remains empty, leaving a net positive charge called a “hole”. The band gap scheme is represented in Figure 2.1.

When the semiconductor lattice has no impurities, the material is named “intrinsic”. In this case, the density of electrons in the conduction band (n_i) and the density of holes in the valence band (p_i) are equal. Since the energy for crossing the band gap is given by thermal excitation, these densities are temperature dependent, and their temperature dependency follows the equation

$$n_i = p_i \propto T^{3/2} \cdot \exp\left(\frac{-E_g}{2kT}\right) \quad (2.1)$$

where T is the absolute temperature, k is the Boltzmann’s constant and E_g is the band gap energy, which is itself a function of temperature. For silicon, at room temperature, the band gap energy is 1.12 eV. The conductivity ρ of a semiconductor depends on both n_i and p_i according to:

$$\rho = e \cdot (\mu_n n_i + \mu_p p_i) \quad (2.2)$$

where e is the electron charge, and $\mu_{n(p)}$ is the mobility of electrons (holes). The mobility



Figure 2.2: Schematics of the silicon lattice in case n-doped (a) and p-doped (b) material.

depends on material and the type of charge carrier. In silicon, for instance, μ_n is $1350 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, and μ_p is $480 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$.

When some atoms of other materials are added to the lattice, the semiconductor is called “doped”, and the impurities are called “dopants”. The addition of impurities can change the amount of charge carriers. For instance, given that semiconductor atoms have four valence electrons, if atoms with five valence electrons are added to the lattice, four of them will create bonds with the semiconductor valence electrons and one will be lightly bond to the atom. This electron can then easily move to the conduction band, increasing the number of free electrons. These impurity atoms are called “donors”. The effect of donor doping is to introduce donor levels at the top of the band gap. A typical donor atom is Phosphorus. When the donor concentration is much larger than the intrinsic carrier concentration, the electrons become the majority charge carrier, and the doped silicon is referred to as n-type. The free electron density, then, is approximately equal to the donor concentration N_D .

On the other hand, if atoms with three valence electrons are added to a semiconductor lattice, one of the semiconductor valence electrons will not form a bond, leaving a hole in the lattice. The density of holes is then increased. These impurity atoms are called “acceptors”. As a consequence of their addition, acceptor levels are introduced at the bottom of the band gap. A typical acceptor atom is Boron. When the acceptor concentration is much larger than the intrinsic carrier concentration, the holes become the majority charge carrier. In this case the doped silicon is referred to as p-type. The free hole density, therefore, is approximately equal to the acceptor concentration N_A . A sketch of the silicon lattice for n-doped and p-doped silicon lattices can be found in Figure 2.2. Sometimes, when the p(n) doping concentration is very high, the semiconductor is referred to as $p^+(n^+)$ -doped.

These two kinds of doped semiconductor materials are the constituents of the p-n junction, which is the basis of semiconductor particle detectors.

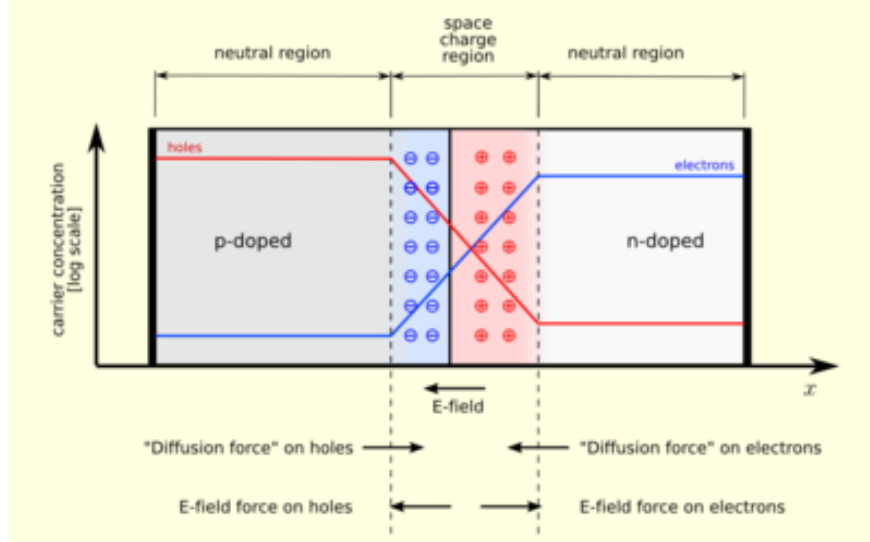


Figure 2.3: Schematics of a p-n junction [52].

2.2 Basic principles of semiconductor particle detectors

The properties of semiconductors, the group of material silicon belongs to, make them ideal materials for particle detection. In the following sections, the principles of the p-n junction will be shown, followed by the description of the interaction with particles and the signal formation. In the final section, the effects of the exposure to particle fluence on the detector's performance will be described.

2.2.1 p-n junction

The p-n junction is formed by combining a p-type semiconductor with an n-type one. Since there is an excess of electrons in the conduction band of the n-type side of the junction, they will move towards the p-type side by diffusion. At the same time, since there is an excess of holes in the p-type side of the junction, they will, in turn, move in the opposite direction, towards the n-type side. Before this migration, the two sides of the junction were electrically neutral. The effect of this movement of charges, then, is the formation of a net negative charge on the p-side and a net positive charge on the n-side of the junction. This charge gradient creates an electric field perpendicular to the junction surface which attracts the charge carriers in opposite direction with respect to their diffusion. Equilibrium is thus reached when the force exercised by the electric field balances the charge carrier diffusion. A sketch of the mechanism that regulates the p-n junction can be found in Figure 2.3.

2.2.1.1 Depletion region

In a p-n junction, the region where the charge gradient is formed is called the depletion region, as it is largely deprived of charge carriers. The depletion region is very important to the constitution of a semiconductor particle detector. In the next section, in fact, it will be shown that when a particle loses some energy in a semiconductor material it releases electron-hole pairs, which then form the signal. In a non-depleted material the electron-hole pairs recombine very fast with the free carriers and their information is lost. In the depletion region, instead, they drift along the electric field lines and produce a detectable signal.

To investigate the electric field intensity and the extension of the depletion region, one must start from Poisson's equation:

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon} \quad (2.3)$$

where V is the voltage, x is the space coordinate (as in Figure 2.3), ρ is the charge density and ϵ is the material permittivity. Given that the donor density in the n-type side of the junction is N_D , the charge density in that region is eN_D . Similarly, since the acceptor density in the p-type side is N_A , the charge density in that region is $-eN_A$. Therefore Poisson's equation will be

$$\frac{d^2V}{dx^2} = -\frac{eN_{D(A)}}{\epsilon} \quad (2.4)$$

for the n(p)-type side of the junction.

We define the extension of the depletion region in the p-type side as x_p , and similarly its extension in the n-type side as x_n . For ease of reference, we set the zero on the x axis at the junction surface, with the p-type side extending in the negative direction. Since

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} \quad (2.5)$$

and the boundary condition is that E is zero at $-x_p$ and x_n , one can integrate E and obtain the relations for the electric field:

$$\begin{cases} E(x) = -\frac{eN_A}{\epsilon}(x + x_p), & x < 0 \\ E(x) = \frac{eN_D}{\epsilon}(x - x_n), & x > 0 \end{cases} \quad (2.6)$$

Since the function describing the electric field must have the same value for $x = 0$ on both sides

$$E(0) = -\frac{eN_A}{\epsilon}x_p = \frac{eN_D}{\epsilon}(-x_n) \quad (2.7)$$

from which we can derive the relation

$$N_Ax_p = N_Dx_n \quad (2.8)$$

To obtain the function describing the potential one must integrate the electric field. For ease of reference, we set the value of the voltage to 0 for $x = 0$. Then we obtain

$$\begin{cases} V(x) = \frac{eN_A}{\epsilon}\left(\frac{x^2}{2} + x \cdot x_p\right), & x < 0 \\ V(x) = -\frac{eN_D}{\epsilon}\left(\frac{x^2}{2} - x \cdot x_n\right), & x > 0 \end{cases} \quad (2.9)$$

The potential difference between the edges of the depletion region is then

$$\Delta V = V(x_n) - V(-x_p) = \frac{e}{2\epsilon} (N_D x_n^2 + N_A x_p^2) . \quad (2.10)$$

This is referred to as the built in bias (V_{bi}), and is typically of the order of few Volts. Using Equations 2.8 and 2.10, the depletion depth is then

$$d = x_n + x_p = \sqrt{V_{bi} \frac{2\epsilon}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} . \quad (2.11)$$

2.2.1.2 Reverse bias

The p-n junction described in the previous section can be used as a particle detector. The intrinsic unbiased depletion region, though, is very small (of the order of few μm) and the electric field is very weak, so the performance of such a particle detector is rather poor in terms of signal speed and strength. One can improve the detector performance, then, by reverse biasing the p-n junction. This, in fact, is most familiar as a diode. Its behaviour is such that, if a voltage is applied in the “forward” direction with respect to the diffusion of the charge carriers (positive on the p-side), a high current is generated, since the potential will tend to attract electrons from the n-side and holes on the p-side, where they are the majority charge carriers respectively. On the other hand, if a voltage is applied in the “reverse” direction (p-side negative), a very small current flows through the junction, since electrons are attracted from the p-side and holes from the n-side, where they are the minority charge carriers.

In the reverse bias condition, the applied voltage is in the same direction as the built-in voltage. Therefore, it will contribute positively to the extension of the depletion region. Starting from equation 2.11, then, we can add the external voltage V to obtain the relation:

$$d = \sqrt{(V + V_{bi}) \frac{2\epsilon}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} . \quad (2.12)$$

The fact that the depletion region can be extended by applying reverse bias is very important, since a large depletion depth is desirable for producing a high signal. Moreover, the higher electric field increases the speed of the charge carriers, and therefore the signal formation. For instance, at a bias of few hundred volts, the charge collection in a 300 μm thick silicon detector can be as fast as few tens of nanoseconds.

Generally, the applied voltage V is much higher than the built-in bias voltage V_{bi} . Also, typically one of the two sides is much higher doped than the other. So, in the case of a p^+-n junction, from Eq. 2.8 most of the depletion region will extend in the n side of the junction, where $N_D \gg N_A$. On the other hand, in a $p-n^+$ junction, most of the depletion

region will form in the p-side, where $N_A \gg N_D$. Defining then N_{eff} as $N_D - N_A$, we can rewrite equation 2.12 as

$$d = \sqrt{V \frac{2\epsilon}{e|N_{eff}|}} . \quad (2.13)$$

Furthermore, the effective doping concentration determines the resistivity ρ of the material according to

$$\rho = \frac{1}{e\mu|N_{eff}|} \quad (2.14)$$

where μ is the mobility of the majority charge carriers (holes for p-type silicon and electrons for n-type silicon). Equation 2.13 can be finally re-written as

$$d = \sqrt{2V\epsilon\mu\rho} . \quad (2.15)$$

From this equation, one can notice that, to increase the depletion depth of a semiconductor detector, we must increase either the reverse bias voltage, or the resistivity of the material, or both.

With increasing reverse bias, the depletion region can extend until it reaches the whole thickness of the detector. In this case, the detector is said to be fully-depleted. Given a detector of thickness D , the minimum bias voltage required to fully deplete it is called depletion voltage (V_{dep}), and it can be calculated as

$$V_{dep} = \frac{D^2}{2\epsilon\mu\rho} . \quad (2.16)$$

2.2.1.3 Leakage current

The current flowing through the semiconductor bulk is called leakage current. Its behaviour with respect to the applied voltage is known as an I-V (or IV) curve. As described in the previous section, the application of a forward bias to a p-n junction increases the leakage current, while a reverse bias maintains the leakage current to a very low level. Nevertheless, if the reverse bias reaches a certain value, called breakdown voltage, the leakage current increases abruptly to very high values. This sudden change of behaviour can be due to two effects: Zener breakdown and avalanche breakdown. In Zener breakdown, valence electrons move to the conduction band due to the high voltage and high doping concentration. This, though, is not the case of high resistivity materials. Avalanche breakdown, instead, happens when the electrons flowing through the junction gain enough energy to create electron-hole pairs through ionization. The newly created pairs can themselves create other pairs and so on in a cascade.

In a stable reverse bias condition, most of the leakage current is produced by thermal excitation of electron-hole pairs. This is known as generation current. It is obvious that this

current depends on temperature. In particular, it follows the relation

$$I \propto T^2 \cdot \exp\left(-\frac{E_A}{kT}\right) \quad (2.17)$$

where E_A is a constant, k Boltzmann's constant and T the absolute temperature [53].

2.2.2 Particle detection

Now that we have seen the basic constituent of a semiconductor detector, the mechanism of particle detection will be shown. As far as this thesis is concerned, the interactions with two kind of particles are investigated: X -rays and charged particles. Regardless of the kind of interaction, the quantity of interest for particle detection is the average energy required to produce an electron-hole pair, often referred to as *ionization energy* with the symbol ϵ . This is different from the band gap and is largely independent of the energy of the incident radiation. This simplification is very important, since the energy released in the material can be converted to the number of electron-hole pairs by simply dividing by the ionization energy. This parameter is observed to vary depending on the material, but generally in doped semiconductors the dopant concentration is not large enough to change its value. For instance, the ionization energy of silicon is 3.63 eV, independent of the doping level. For ease of reference, when the charge released is measured in terms of electron-hole pairs produced, the units are called electrons (e^-).

2.2.2.1 Interaction with X -rays

Depending on the atomic number of the material, photons can have different interactions. With soft X -rays of energy below 20 keV, though, in most semiconductor materials the main interaction process is photoelectric absorption. In this case, the photon is completely absorbed by one material atom. The energy of the photon is then collected by a shell electron and converted into kinetic energy according to

$$E_{e-} = h\nu - E_b \quad (2.18)$$

where E_b is the binding energy of the electron's original shell. The emitted electron, called "photoelectron", then releases its energy through electron-hole pair production. The vacancy left by the electron is then filled by other electrons in the valence or conduction band, leading to the emission of other X -rays, which in most cases are absorbed as well. Most of the time, therefore, all the energy of the X -ray is absorbed within a small distance from the interaction point. Therefore, if the photons are monoenergetic and all the signal is collected,

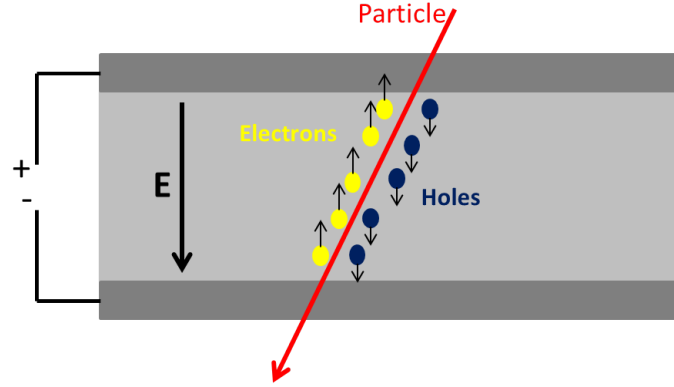


Figure 2.4: Electron-hole pairs released in silicon by a crossing particle.

the resulting spectrum will show a peak, known as full-absorption peak (see Section 3.4).

2.2.2.2 Interaction with charged particles

Heavy charged particles interact with semiconductor materials in two ways: elastic scattering with nuclei or inelastic scattering with atomic electrons. The former is responsible for radiation damage (see next section), while the latter is the main source of energy loss. The amount of energy released in the material per unit length, dE/dx , is described by the Bethe-Bloch formula as a function of the particle energy. This function shows a broad minimum for energies between 0.1 and 1 GeV and then undergoes a slow relativistic rise. For this reason, particles with energy in this range are referred to as Minimum Ionising Particles (MIPs). These particles cross a semiconductor bulk of a few hundreds of micrometers without losing a significant amount of energy. This property is essential for the construction of a tracking system, since a 3-dimensional picture of the tracks require the particles to pass through multiple layers of detectors. A simple representation of the mechanism is shown in Figure 2.4.

When the particle transverses a semiconductor bulk, the energy loss follows a distribution called a Landau distribution. The peak of this distribution is the Most Probable Value (MPV), and it is derived from the Bethe-Bloch formula. For silicon detectors, the energy loss per micrometer is about 270 eV. Therefore, given that the ionization energy in silicon is 3.6 eV, the most probable number of electron-hole pairs released per micrometer is 76. For instance, a particle transversing a 300 μm thick detector will release charge following a Landau distribution with its MPV equal to $\sim 22000\text{ e}^-$.

2.2.3 Radiation damage

Particles transversing a semiconductor detector produce, along with a signal, some level of damage within the sensor itself. The knowledge of these effects is crucial for the design of a detector, since it affects the detector performance. The radiation damage can be divided in two types: surface damage and bulk damage. The former is located at the oxide layers that are generally deposited at the surface of the detector during its manufacture. Its treatment, though, is beyond the scope of this thesis. The bulk damage, instead, is responsible for the signal degradation, and its behaviour has been investigated extensively [54] [55].

2.2.3.1 Bulk damage

The bulk damage is due to the non-ionizing energy loss (NIEL) interactions of the crossing particles with the lattice atoms. If the energy transferred to the atom in this kind of interaction is sufficiently large, the atom is removed from the crystalline lattice. In this case, the lattice is characterized by an empty site (vacancy) and an atom displaced from its site (interstitial). The pair of vacancy and interstitial is called a *Frankel* pair. The minimum energy required for a particle to produce this effect depends on the nature of the particle itself. For instance, whilst for protons and neutrons this energy is about 110 eV, for electrons it is as high as 260 keV. Therefore, electrons with a certain energy produce less damage than heavier particles with the same energy. If they have enough energy, the displaced atoms can then cause other atoms to be removed from the lattice, resulting in clusters of defects. Nevertheless, the displaced atoms are mobile in the silicon lattice, and in some cases vacancies and interstitials can recombine leaving no damage. A typical irradiation event is shown in Figure 2.5.

The damage caused by the integrated flux of particles of a given energy and nature can be related to the flux of a reference particle. The commonly used reference particle is a 1 MeV neutron. Therefore, for every particle at a certain energy, there is a factor, called the *hardness factor* (k), that relates its damage in terms of the 1 MeV neutron equivalent flux. The unit used for quantifying bulk damage, then, is the 1 MeV neutron equivalent per centimeter square ($n_{eq}cm^{-2}$).

The main visible effects of bulk damage are the change in doping concentration, the change in leakage current and the change in charge collection efficiency.

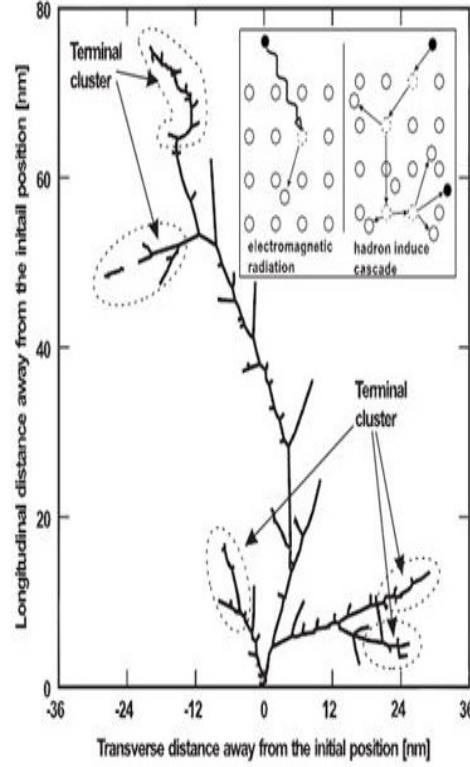


Figure 2.5: Example of a typical recoil-atom track as a consequence of hadron irradiation. Top right: details of the effect on lattice atoms [54].

2.2.3.2 Change in effective doping concentration

The combination of a vacancy with a dopant atom can cause the removal of the doping levels, reducing the dopant concentration. This effect works similarly for donors and acceptors, and it is proportional to the doping concentration. Therefore, it falls exponentially with the fluence. In addition, some defects can form negatively charged di-vacancy complexes which act as acceptors. The increase in number of acceptors produced by this effect has been observed to be linear with the fluence [56]. The total effect of the fluence ϕ on the effective doping concentration is then

$$N_{eff}(\phi) = N_{D,0} \cdot \exp(-c_D\phi) + N_{A,0} \cdot \exp(-c_A\phi) - \beta\phi \quad (2.19)$$

where $N_{D(A),0}$ is the initial donor (acceptor) concentration, $c_{D(A)}$ is the rate of donor (acceptor) removal and β is the rate of acceptor creation.

In the case of an n-type bulk, where $N_{D,0} \gg N_{A,0}$, the initial effective doping concentration is approximately equal to the initial donor concentration, and therefore the relation above can be re-written as

$$N_{eff}(\phi) = N_{eff,0} \cdot \exp(-c_D\phi) - \beta \phi \quad (2.20)$$

From this equation we can infer that, with increasing fluence, there will be a point where N_{eff} equals 0, i.e. the density of acceptors is the same as the density of donors and the

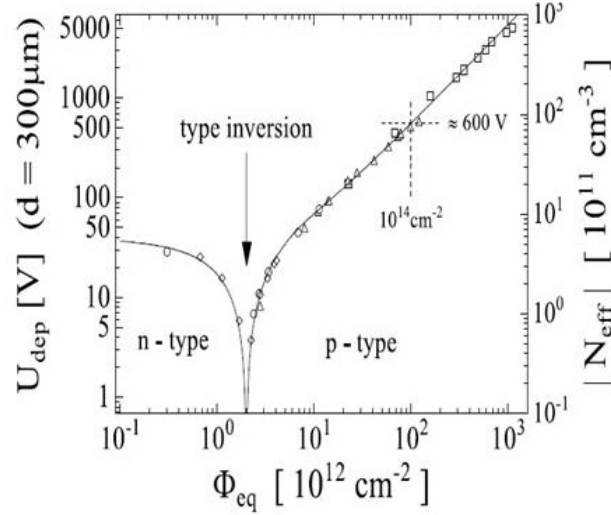


Figure 2.6: Depletion voltage and effective doping as a function of irradiation fluence [54].

detector is intrinsic. This is called the inversion point. After this fluence, in fact, the acceptor concentration becomes higher than the donor concentration and the detector changes into p-type. This effect is therefore known as type-inversion. This behaviour can be seen in Figure 2.6, where the depletion voltage (linearly dependent on $|N_{eff}|$, as seen in Equation 2.16) is shown as well.

As mentioned before, the defects due to irradiation can move within the semiconductor lattice. For this reason, after irradiation, the effective doping concentration is not stable, but it changes with time. This process is known as annealing and it depends on temperature. There are two effects related to the annealing: the short, or “beneficial”, annealing and the long, or “reverse”, annealing. In the beneficial annealing process, the effective doping concentration (after type-inversion) decreases, while in the reverse annealing the effective doping concentration increases. Since the beneficial annealing happens in a shorter time than the reverse annealing, the behaviour of N_{eff} with respect to annealing time is such that it decreases initially until it reaches a minimum, and then it increases until it becomes stable. This trend of N_{eff} with annealing time and temperature is crucial for establishing an annealing procedure after irradiation. The best operational condition, in fact, is when the depletion depth is maximized, and, recalling equation 2.13, the depletion depth is inversely proportional to the square root of N_{eff} . For this reason, the common procedure after irradiation is to anneal the detectors until N_{eff} is at minimum. Generally, this is done by keeping the devices at 60 °C for 80 minutes, or at 80 °C for 60 minutes, or at room temperature for 10 days.

2.2.3.3 Change in leakage current

The defects created during irradiation form new energy levels in the middle of the band gap. These increase the probability for charge carriers to be thermally excited and move to the valence band. For this reason, the leakage current is enhanced after irradiation. It has been shown that the leakage current per unit volume increases linearly with the irradiation fluence. We can then estimate that

$$\frac{\Delta I}{V_{depleted}} = \alpha \phi \quad (2.21)$$

where ΔI is the increase in leakage current, $V_{depleted}$ is the detector depleted volume and α is called the *reverse current damage factor*. Recent studies have shown this parameter to be in the range 4 to 6×10^{-17} A/cm at 20°C [57].

During the annealing process, the leakage current decreases, but the microscopic explanation for this effect is still not satisfactory [54].

2.2.3.4 Change in charge collection efficiency

The charge collection efficiency (CCE) is the probability for charge carriers released by ionization from a particle to be collected and produce signal in the detector. This parameter is significantly affected by irradiation. The defects caused by irradiation, in fact, can act as trapping centres for the charge carriers. This means that the carriers, while drifting in the semiconductor bulk, are trapped by these defects, and contribute only partially to the signal. For this reason, the total signal itself is reduced, and therefore the charge collection efficiency too. This effect can be parametrized by the *effective trapping time* τ_{eff} , which is related to the probability over time for the carriers to be trapped. This parameter is different for electrons and holes and it is inversely proportional to the fluence [58]. To reduce charge trapping, the signal formation time must be made as short as possible. To reduce the effect of the charge trapping, then, the signal formation time must be made very short compared to the effective trapping time. This is achieved by increasing the bias voltage to very high levels (sometimes of the order of thousands of Volts).

2.3 Hybrid detectors

Up to now, we have discussed the sensing component of the semiconductor detectors, i.e. the p-n junction. This is where the signal is produced. For a detector to be operative, though, the signal must be collected, processed and driven to the periphery of the detector by an

appropriate read-out chain. The design and implementation of such a read-out circuitry, therefore, is a crucial process in detector fabrication.

In many high energy particle physics experiments, the tracking system is based on silicon detectors. If the experimental conditions require them to be extremely fast and radiation tolerant, a high bias voltage can be applied to strengthen their signal, as shown in the previous section. The read-out electronics, though, work at low voltages (of the order of few Volts). To prevent high voltage from damaging the read-out circuitry, then, the standard fabrication procedure is to produce the sensing component and the read-out component separately, and then merge them together in a process known as *hybridization*. These detectors are therefore called *hybrid* detectors. The ATLAS experiment at CERN, along with many other experiments, makes wide use of these detectors for its tracking system [59, 60].

In this section, the basic components and principles of the read-out process will be shown, followed by a brief description of the two main kinds of hybrid detectors used in particle physics: pixel and strip silicon detectors.

2.3.1 Read-out electronics

As explained in the previous section, the signal in a semiconductor detector is produced by the charge carriers moving through the electric field. These produce a current which induces a voltage variation at the edges of the detector. The high bias voltage is then filtered out, generally through a capacitor, and the signal variation due to the charge movement is collected and processed.

2.3.1.1 Common electronic components

Typically, the first step of signal processing is performed by a charge sensitive preamplifier, a component which receives a charge input and returns a voltage output whose amplitude is related to the amount of charge collected. The signal is then generally shaped by a shaping amplifier, which differentiates and amplifies the preamplifier signal. The output of the amplifier can have different shapes, typically triangular or Gaussian. Nevertheless, for many applications (including tracking), the signal is pulse-shaped. This means that it rises for a certain time and then falls until it returns to baseline. The duration of the pulse is regulated by the *shaping time constant* of the amplifier. The amplifier also acts as a filter for high and low frequency noise. The signal processing system described so far is known as a charge sensitive amplifier (CSA). The pulse height of the CSA is related to the charge collected from the original signal input. Generally this relation is linear, and the linearity factor is called *gain*.

In tracking applications generally, after the amplification stage, the output of the CSA goes through a discriminator (or comparator). This component produces a digital signal if the input signal is higher than a certain threshold. When the read-out system deals with many different channels, it is unfeasible to use the analogue signals from all the amplifiers, and therefore comparators are necessary to digitalize the signal. In addition, in many comparators the digital signal starts when the amplifier output is above the threshold level and stops when the signal returns below the threshold. The length of the comparator output, then, is called Time over Threshold (ToT). This is related to the signal height, and therefore, ultimately to the original charge collected. The dependence of the ToT on the charge collected, though, is often non-linear.

One important feature in all electronics components is the noise. There are several possible sources of noise. A full discussion on the noise sources, though, is beyond the scope of this thesis. Nevertheless, it is important to outline that the noise is highly correlated with the capacitances in the system, including the input capacitance of the collecting diode [61]. In particular, the higher the input capacitance, the higher is the noise.

Many components of the read-out circuitry are active components, and therefore a certain voltage (of the order of few Volts) must be applied to guarantee their operation. This is generally done inside the chip by means of specific digital-to-analog converters (DACs). These components receive a digital signal from the read-out system and convert it to a fixed analog voltage. This property can be very useful, as one can regulate the voltages of some read-out components to improve the operational behaviour of the chip. For instance, the shaping time can be modified by setting the DAC which operates on the feedback voltage. This voltage regulates the feedback current and ultimately the falling edge of the signal pulse.

In general, a read-out chip has a series of DACs, and the user must set these DACs to the values which guarantee a good operational behaviour. Some of the typical features that are required are a good signal-to-noise ratio (the ratio between the collected signal and the read-out noise), uniform threshold and uniform gain for all the pixels, but more features can be required depending on the specific task the chip is designed for. The operation of finding the right set of DAC values is called DAC setting, and it is assumed to be performed before taking data.

2.3.1.2 Time-walk

An important feature of the read-out system, common to many applications, is the *time-walk*. This effect is related to the dependence of the time-stamp of the pulse, i.e. the time at which the pulse reaches the threshold, on its amplitude. The output of many CSAs, in fact, is a triangular pulse with constant peaking time, and therefore the slope of the rising edge of the pulse increases with the amplitude. This means that the time at which the

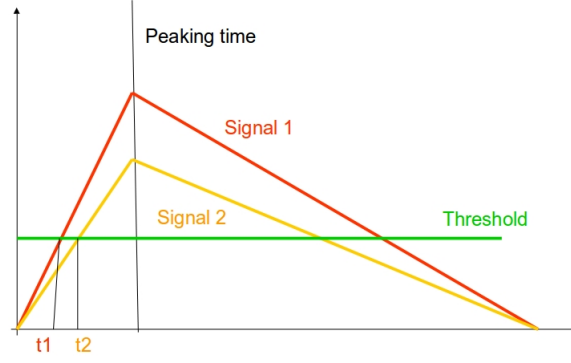


Figure 2.7: Time-walk representation. The peak of signal 1 is higher than signal 2, and therefore it crosses the threshold before signal 2.

pulse crosses the threshold depends on the amplitude of the pulse itself (see Figure 2.7). In particular, the time-stamp is inversely proportional to the difference between the signal amplitude and the threshold. This effect, if present, must be considered with care, since for small signals the time-stamp can be significantly delayed. For instance, at the LHC, since the bunch crossing time is 25 nanoseconds, the time-walk can not be larger than that value, otherwise some hits can be associated with the wrong event.

After the digitalization, the outputs from different channels are handled by read-out chips. In general, the read-out circuitry of a detector is implemented in an Application-Specific Integrated Circuit (ASIC). The design of such a circuit is a complicated task and its discussion is beyond the scope of this thesis.

2.3.2 Detector design

The most common use for silicon detectors is in tracking. This task requires a high spatial resolution, therefore the silicon detectors must be divided into small units. The two most common geometries are pixels, with a bi-dimensional resolution, or strips, where the resolution is mono-dimensional. This is generally achieved by etching the p-n junction on its surface, where the read-out circuitry is placed. The doped silicon on that side, then, is typically covered with aluminum to create a contact with the read-out components. If the aluminum is placed directly over the silicon, the devices are said to be “dc-coupled”. If, instead, a layer of dielectric material is deposited in between, they are “ac-coupled”. The extra layer in the ac coupling prevents the leakage current to flow to the electronics. In addition, some insulator, commonly SiO_2 , is deposited in the gaps between the pixels or strips. Finally, to prevent breakdown effects of the electric field at the edge of the detectors, rings of highly doped silicon, called *guard rings*, are placed around the active area.

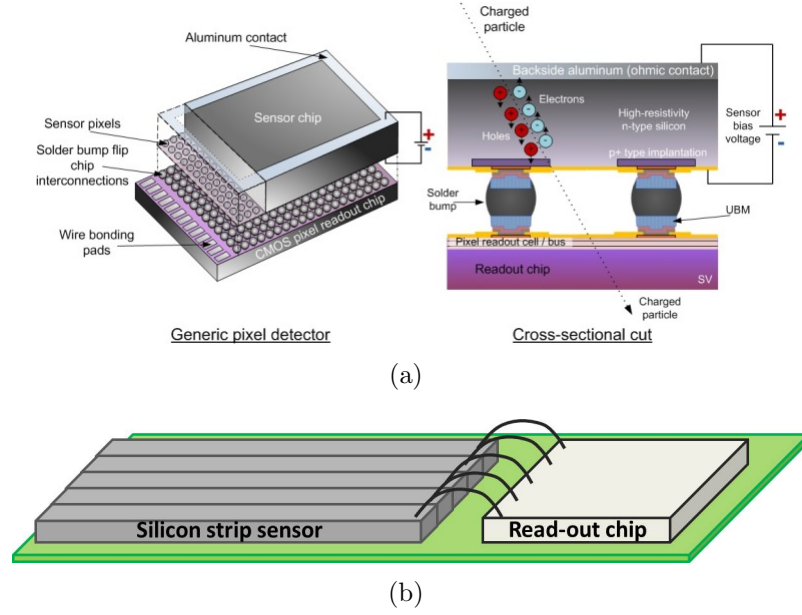


Figure 2.8: (a) Sketch of the bump bonding process and read-out mechanism of a pixel detector [64]. (b) Sketch of the wire bonding for a strip detector.

When the detector is etched in pixels or strips, each channel acts as a separate entity. The electric field assures that the charge carriers produced within a pixel's volume move towards the edge of the pixel itself. The same applies for strips. The signal is then produced immediately when the charge carriers start moving, and it is recorded as an effect of this current on the voltage at the edge of the sensor. The fact that the signal is then recorded only in the pixel where the charge is collected, and not in neighbouring pixels, is guaranteed by Shockley-Ramo's theorem [62]. When the charge is released close enough to the pixel boundary, though, not all of it is collected by that pixel itself. Because of thermal motion, in fact, charge carriers can move perpendicularly to the electric field lines and reach other pixels. This effect is known as *charge sharing* [63].

Because of their geometries, the hybridization process of pixel and strip detectors is different.

2.3.2.1 Pixel detectors

To connect every pixel of the sensitive silicon bulk to its corresponding pixel in the read-out chip, the sensor and the chip must be overlaid. To assure the electrical contact for all channels, a small metal bump is deposited on the surface of everyone of them. Every bump is then soldered to the corresponding pixel of the read-out chip, forming what is called a *bump-bond*. This process is therefore referred to as *bump-bonding*. This procedure is extremely delicate, and the chance of failure is quite high. Moreover, with this configuration, in a tracker environment the read-out chip adds extra material presented to the particle track. This increases the probability of scattering for the tracked particles, and therefore affects

the tracking resolution. A sketch of a pixel detector read-out configuration can be found in Figure 2.8(a).

2.3.2.2 Strip detectors

In the case of strips, the hybridization process is much less complicated. The strips, in fact, can be connected to the read-out chip by thin wires, and the chip itself can be placed on the side of the sensing silicon bulk. This process is then called *wire-bonding*. The fact that strip detectors are easier to produce than pixel detectors makes them much less expensive when covering large areas of detectors. This is the reason why, in many experiments, the outer layers of the tracking system are made of strip detectors. A sketch of a silicon strip read-out configuration is found in Figure 2.8(b).

2.4 CMOS detectors

Hybrid sensors are very good candidate for tracking systems in high energy particle physics experiments. Nevertheless, they are not the most cost-efficient option. In the pixel case, for instance, the bump bonding process is quite expensive and subject to a failure rate. For this reason, a new technology has been considered: the CMOS detectors.

2.4.1 The MOSFET

The structure at the base of the CMOS technology is the metal-oxide-semiconductor field-effect transistor (MOSFET, or simply MOS). The MOS is a special type of transistor which is made with four terminals: gate, source, drain and body (or well, or substrate) (see Figure 2.9) [52]. The gate is generally made with polysilicon, source and drain can be made with either n-type or p-type silicon. In the first case the transistor is known as nMOS, in the latter case as pMOS. The body is made with doped silicon as well, but the doping type is complementary to the doping type of the source and drain. The doping is therefore p-type for a nMOS transistor and n-type for a pMOS transistor. In addition, there is an insulating layer between the gate and the body.

As a field effect transistor, the conductivity between the drain and the source is regulated by the voltage between the gate and the body. This feature can be used for amplifying or switching electronic signals. For this reason, MOS transistors are widely used in electronic applications.

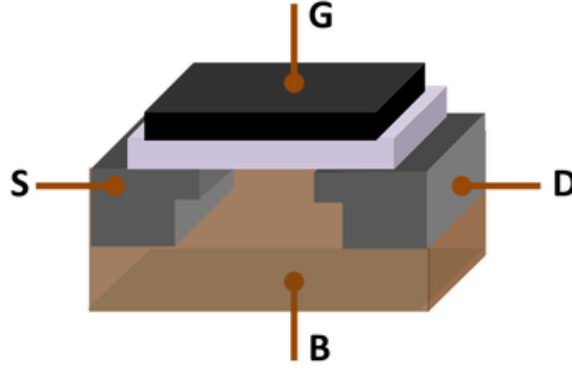


Figure 2.9: Sketch of a MOSFET with gate (G), body (B), source (S) and drain (D) terminals. The gate is separated from the body by an insulating layer (pink) [52].

2.4.2 Standard CMOS technology

CMOS (Complementary MetalOxide Semiconductor) is a technology developed for electronic circuits. It is formed by the union of the pMOS and nMOS transistors. Because of their flexibility, CMOS devices have been broadly used in electronic applications, including pixel sensors. In these sensors the read-out electronics are implemented into the silicon sensing substrate itself. Because of this, these devices are much easier to produce than the hybrid ones. The significant cost-reduction they bring makes them ideal for covering large areas inside the detector. Indeed, these sensors have been characterized as high precision tracking and vertexing devices, due to fine granularity and low material budget [65, 66]. A sketch of a CMOS pixel sensor is shown in Figure 2.10(a).

In the standard CMOS technology high reverse bias voltage cannot be applied, since the electronics sit in the silicon bulk itself. Therefore, depletion occurs only in the naturally built-in depleted layer, and most of the charge released by a MIP is collected by diffusion. The signal therefore is much smaller and slower than in standard hybrid detectors. This fact renders these devices ineffective in an environment such as the ATLAS experiment, since charge diffusion happens in few microseconds. For this reason these sensors cannot meet the performance requirements of the ATLAS tracking system.

Furthermore, fast charge collection is an important characteristic for devices to be radiation tolerant. One of the most significant effects of radiation, in fact, is charge trapping, as described in Section 2.2.3.1. Since the probability of trapping is reduced with faster charge carrier speed, collection via drift is highly favoured with respect to diffusion.

Given the strict requirements for the strength and speed of the signal, CMOS technology can be a good candidate for the ATLAS tracking system only if a larger depletion region can be achieved.

2.4.3 CMOS in High Energy Particle Physics

According to equation 2.15, a larger depletion width can be achieved by increasing the reverse bias voltage or the material resistivity. The CMOS sensors where high bias voltage (higher than few tens of volts) can be applied are called HVCMOS, while those made with high resistivity substrate (higher than few hundreds of $\Omega\cdot\text{cm}$) are called HRCMOS. In particular, in HVCMOS detectors a deep n-well is introduced to protect the electronics from the high voltage applied to the bulk (see Figure 2.10(b)) [67]. More generically, this novel type of CMOS is referred to as Depleted CMOS pixel sensors or Depleted Monolithic Active Pixel Sensors (DMAPS).

Depending on the amount of read-out circuitry implemented in the silicon bulk, CMOS sensors can be classified in three categories:

- Passive CMOS sensors: no read-out is implemented inside the silicon bulk, thus all the signal processing and digitalization is performed by a front-end chip.
- Active CMOS sensors: the first stages of signal processing and digitalization are implemented inside the bulk, but not completely. Therefore a front-end chip is still needed.
- Fully monolithic CMOS sensors: all the signal processing and digitalization is implemented, therefore no front-end chip is required.

An important parameter to take into consideration when designing a CMOS device is the *fill factor*, i.e. the ratio between the surface of the deep n-well and the total surface. In addition, there are two possible solutions for designing the deep n-well: either it surrounds the electronics or it is implemented outside the electronics. In the first case, the deep n-well must cover a significant portion of the pixel in order to include all the electronics. For this reason, this implementation of the CMOS technology is referred to as *large fill factor*. In the latter case, the deep n-well must be small compared to the whole pixel area, and therefore this implementation is called *small fill factor*.

The ATLAS experiment is considering these devices for the upgrade phase in the ITk Detector (see Section 1.4.1). The aim is to introduce CMOS detectors in an eventual 5th layer of barrel pixels. In this case, the expected fluence will be $1.5 \times 10^{15} n_{eq}/\text{cm}^2$. For this purpose, a comprehensive study of these devices is needed, to fully characterize their performance and verify that they meet the ITk requirements.

Part of this thesis follows this characterization work on three different kinds of CMOS detectors. A detailed description of these devices, then, will be presented in Chapter 4, along with the results of their characterization.

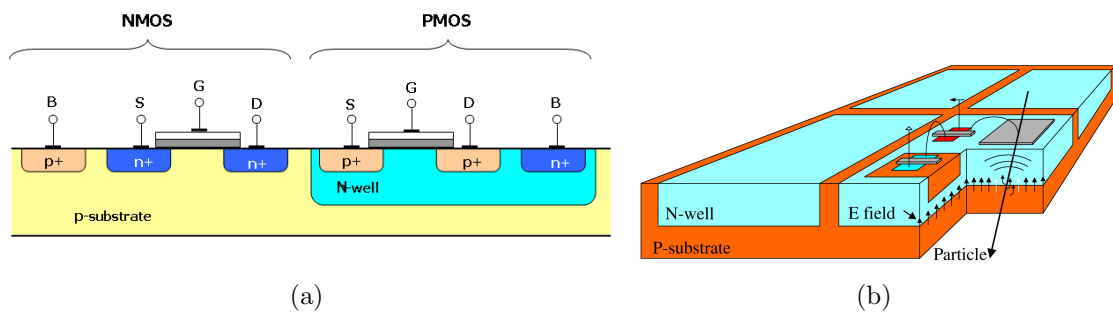


Figure 2.10: (a) Standard CMOS sensor layout (from side). (b) Layout of the CMOS modified process for high bias voltage [67].

Chapter 3

Characterization methods for silicon detectors

This chapter is dedicated to the experimental methods used for the characterization of silicon detectors. In order to evaluate if a new technology is suited for the HL-LHC, many tests must be completed to study its performance. These tests can range from simple electrical tests, to exposure to radiation sources or particle beams. It is also critical to determine if the new technology can withstand the radiation hardness expected at the HL-LHC.

The next chapter will provide the results obtained with some of these tests on CMOS prototypes. Before showing the outcome of these tests, though, it is important to illustrate the techniques and the methods used in each of them. This chapter will describe in detail the tests performed. Every section, then, will be dedicated to a specific kind of test.

More specifically, these are:

- Laser (Front and Edge Transient Current Technique)
- IV measurements
- Gain and noise measurements
- Exposure to X -ray sources
- Exposure to ^{90}Sr sources
- Pixel relative efficiency with radiation sources
- Test beam
- Time-walk measurements.

A detailed description of each test will be presented in the following sections.

3.1 Laser system

One type of study for sensor characterization is based on a laser technique called the Transient Current Technique (TCT) [68]. In this technique, a short-pulse laser (a few nanoseconds duration) is used to mimic the fast charge release of a particle. Precision motion stages move the detector under investigation in the two directions perpendicular to the laser beam, whilst the focal system can be moved in the third direction to focus the beam to micron sizes.

In general, when laser light is shone through a semiconductor, the photons produced by the laser undergo photo-absorption in the semiconductor. The charge released by photo-absorption, then, produces the signal. The absorption length depends on the semiconductor material and the wavelength of the light.

The system used in this thesis uses two laser wavelengths, 640 nm (red) and 1064 nm (infrared). The reason to use two lasers with different wavelengths can be explained by viewing the absorption length in silicon as a function of the wavelength (Figure 3.1). From this plot, in fact, it can be noticed that the absorption length of the 640 nm laser in silicon is quite short, of the order of few micrometers, and then it increases significantly reaching almost one millimeter for the 1060 nm laser [69]. Thus, thanks to this property, the user can choose either to produce a very localized charge deposit (with the 640 nm red laser), or to release the charge rather uniformly along the laser axis (with the 1060 nm infrared laser). The choice between the two wavelengths depends on the nature of study one wants to perform, as will be shown later.

Finally, depending on the direction of the laser with respect to the detector, the user can perform two kinds of tests: Front-TCT and Edge-TCT.

3.1.1 Front Transient Current Technique

In a TCT system, when the laser axis is perpendicular to the chip surface, the technique is referred to as Front-TCT. This technique is generally used to verify the uniformity of charge collection in different areas of the pixel. In the case of a red laser, the portion under investigation is the superficial layer, while with the infrared laser the charge can be deposited deeply inside the bulk. A sketch of this mechanism is shown in Figure 3.2. In both cases, charge is not released with the same process as with MIPs. The results collected with this technique, therefore, are only indicative of the device's charge collection behaviour in a tracking system.

Some complications with this technique can occur if the chip surface is metalized. In this case, the metal absorbs the infrared laser light and reflects the red laser light. For both wavelengths the areas where the metalization is present appear as regions of lower or even

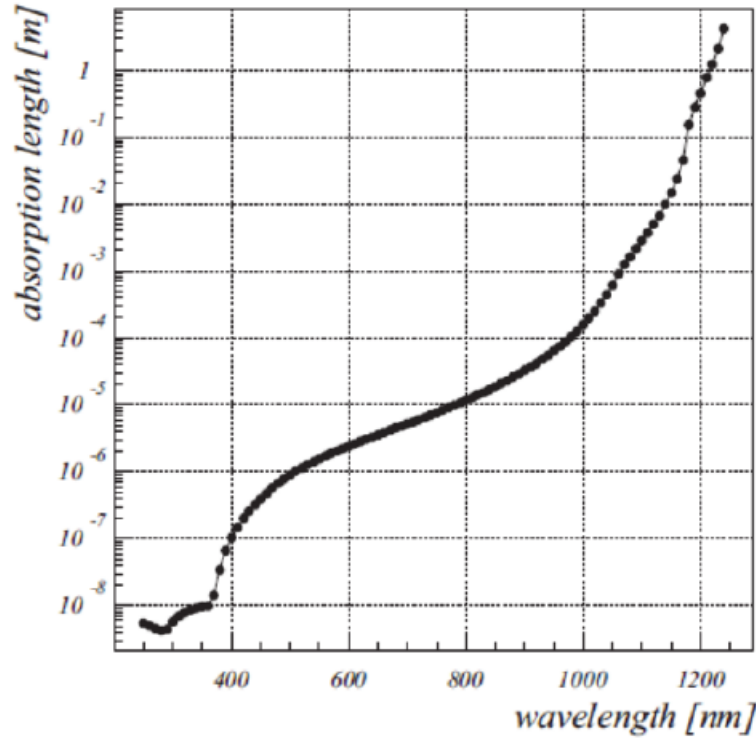


Figure 3.1: Absorption length as a function of wavelength for silicon [69].

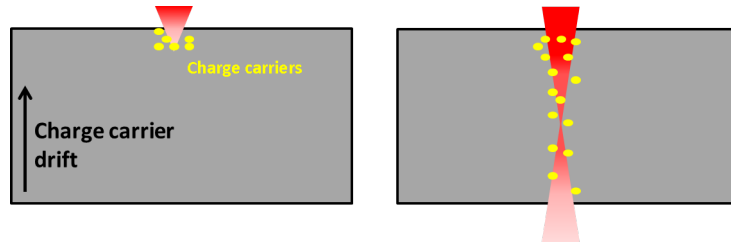


Figure 3.2: Sketch of the front-TCT technique with a red laser (left) and an infrared laser (right)

null signal, even if there is no charge loss in the sensitive bulk.

3.1.2 Edge Transient Current Technique

The most common way to use the TCT system is the edge-TCT. In this case, the laser is oriented onto the side of the detector itself (see Figure 3.3). This configuration is very helpful to investigate the extension of the depletion region. The charge can be released deep inside the silicon bulk, from the sensor surface, where typically the read-out components are placed, to the back of the sensor. With this procedure, the signal can be detected as long as the charge is released inside the depleted region. The extension of the signal region, therefore, corresponds to the extension of the depletion region. To guarantee a uniform charge release along the laser axis, the infrared laser is preferable to the red laser. For this

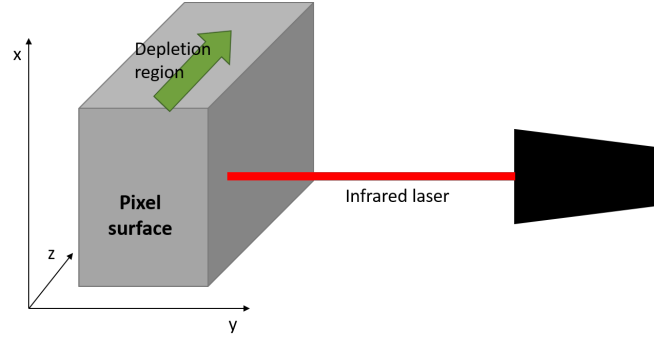


Figure 3.3: Sketch of the edge-TCT technique.

reason, in all the Edge-TCT measurements performed in this thesis, the infrared laser has been used.

The Edge-TCT technique allows to compute the depth of the depletion region. This is a very important feature for a semiconductor detector, since the depletion depth is related to the MIP signal distribution, as explained in Section 2.2.2.2. Generally, to calculate the depletion depth, one plots the signal height as a function of the laser position in the direction perpendicular to the surface (z axis in Figure 3.3) and then compute the Full Width Half Maximum (FWHM) of the obtained distribution. The depletion depth is a function of the reverse bias voltage and the resistivity of the bulk (see Equation 2.15).

Some limitations of the Edge-TCT technique may come from the read-out board. In fact, if the board is designed in such a way that the device is surrounded by board materials and components, the path of the laser towards the device will be obstructed. The results, therefore, are likely to be affected as well. In designing a board for Edge-TCT one should leave some empty space for the laser to be shone to the edge of the sensor.

3.1.3 Laser resolution

The laser system used in this thesis is located in the Oxford Physics Micro-structure Detector facility (OPMD) at Oxford [70]. The resolution of the focal system has been investigated both with the red laser for the Front-TCT and with the infrared laser for Edge-TCT.

The resolution at a fixed focal distance can be computed as follows. First, a region must be found on the sensor where an abrupt change of signal is expected, i.e. the sensor's edge or a metal surface. When moving the detector, the laser crosses the boundary of such a region and the signal shows a steep rise. Assuming that the laser spot intensity is Gaussian, the observed distribution can be described by an error function:

$$f(x) = A \cdot \int_{-\infty}^x \exp\left(\frac{-(y - x_0)^2}{2\sigma^2}\right) dy + B \quad (3.1)$$

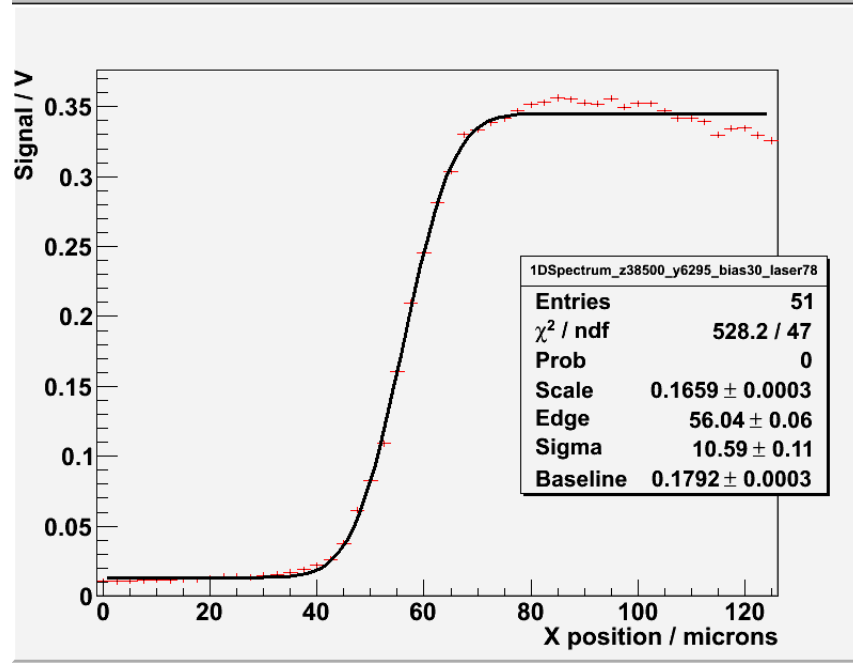


Figure 3.4: Example of the behaviour of the signal in a boundary region of the pixel. The graph has been fitted with an error function.

where A is a scale factor, x_0 is the position of the edge of the sensitive region, σ is the Gaussian standard deviation and B is a baseline shift factor (to account for noise).

The sigma parameter extracted from this fit is considered a measure of the resolution. An example of such a fit is shown in Figure 3.4. The resolution is then plotted as a function of the focal system position. The resulting plot shows a minimum where the focusing is best. This plot can also be fitted with a second order polynomial to have a smooth estimation of the focal position and the minimum resolution value.

This procedure has been carried out on the red laser in the OPMD by performing Front-TCT exposure (Figure 3.5(a)). The computed minimum resolution is $3.3 \pm 0.5 \mu\text{m}$. The resolution of the infrared laser has been computed by performing Edge-TCT exposure (Figure 3.5(b)), and the minimum value has been estimated to be $9.3 \pm 0.1 \mu\text{m}$. The reason why the infrared laser shows a worse resolution is due to the fact that its absorption length is larger. Because of this, the photon interactions are distributed in the silicon bulk and are affected by diffusion leading to a broader path.

3.1.4 Laser power

The laser in the OPMD is also provided with a threshold mechanism to regulate the laser power [68]. The calibration of the laser power has been performed by the vendor and it is found to be linear within a wide range. The relationship between laser power and charge released in a detector, though, is not the same for all the possible detectors, as it depends on

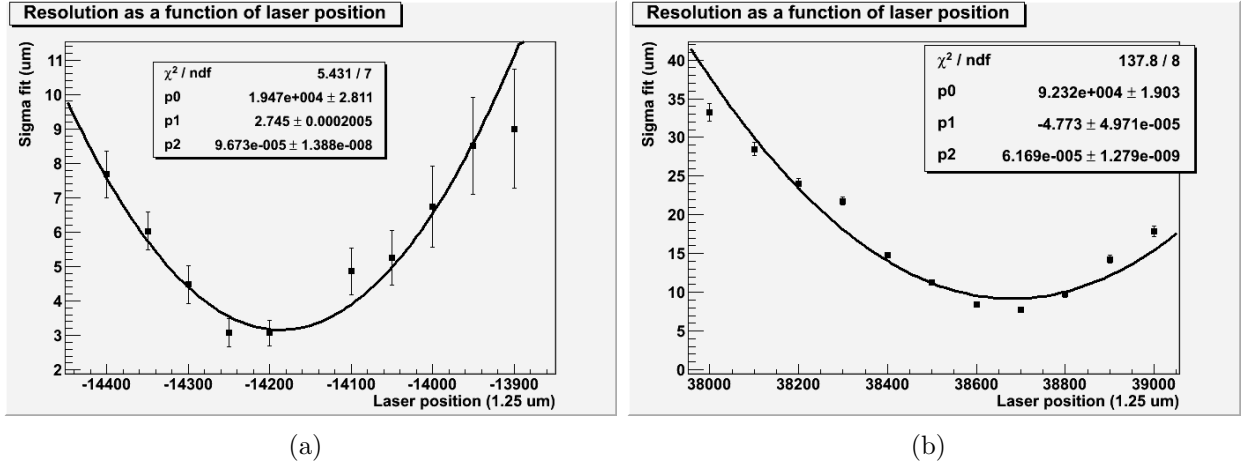


Figure 3.5: Resolution as a function of the focal system position for the red (a) and the infrared (b) laser.

several conditions. For instance, with Front-TCT it depends on the level of metalization on the device's surface, while in Edge-TCT it depends on the amount of silicon the laser beam goes through in its path (if the investigated section is not exactly on the edge of the device). For this reason, the laser power is always regulated with the device under test. This means that, if one wants to release a certain amount of charge in a specific device with the laser, the laser power is varied until the device's output corresponds to the specified amount of signal.

3.2 IV measurements

As explained in Section 2.2.1.3, the leakage current is an important feature of a p-n junction. Silicon detectors are based on a reverse-biased p-n junction. In this case, as the reverse bias increases, the leakage current remains very low until a certain voltage, known as breakdown voltage, where the leakage current increases abruptly. Such an increase in leakage current affects the detector performance, as it increases the noise and the power consumption. The measurement of the breakdown voltage, therefore, is crucial for a semiconductor detector, since it limits the operational conditions of the detector.

The plot of leakage current as a function of reverse bias voltage is known as an IV curve. In the OPMD lab in Oxford, the measurement of such a plot is performed by means of a Keithley 2410 source meter, which has a nominal relative resolution of 0.012% [71]. Most of the measurements are performed in lab conditions, i.e. 24 $^{\circ}\text{C}$ and 40 % humidity.

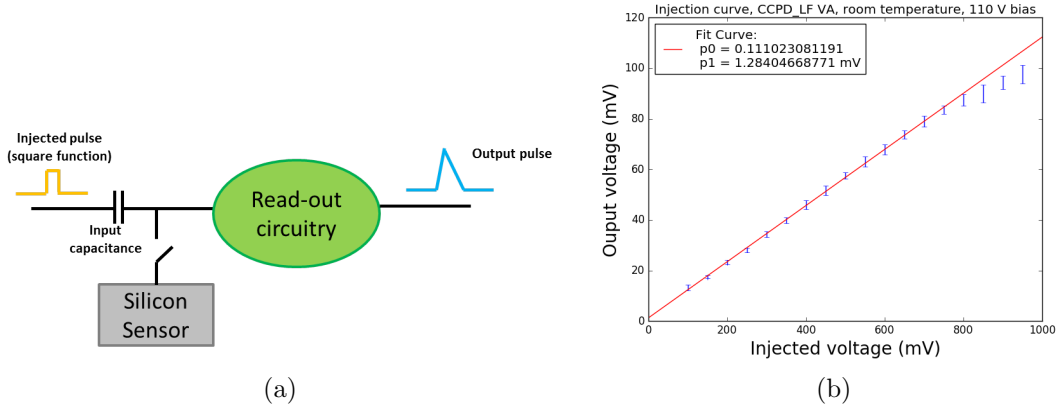


Figure 3.6: (a) Scheme of the charge injection procedure to measure the gain of the read-out circuit. The height of the output pulse is related to the height of the injected pulse, which defines the injected charge. (b) An example of a gain curve with a linear fit.

3.3 Gain and Noise Measurements

The gain is an essential parameter in a read-out circuit, since it allows to relate the measured output to the collected charge (as explained in Section 2.3.1.1). A common procedure to measure the gain is by charge injection. This procedure consists of injecting a certain amount of charge by sending square pulses to a capacitor at the read-out circuitry input. The amount of injected charge can be calculated by the height of the square waves and the value of the input capacitance. The mean output, then, is plotted as a function of injected charge. A scheme of this procedure can be found in Figure 3.6(a), along with an example of a gain curve (Figure 3.6(b)).

Another important feature of the read-out electronics is the noise, as explained in Section 2.3.1.1. To quantify the noise of a device with an analogue output, one must measure the fluctuations on the baseline. To do so, the output waveform is recorded at random times with no signal induced, and the maximum value is extrapolated. Given the random nature of noise, the distribution of maximum values is compatible with a Gaussian function. One can therefore compute the mean of the maximum distribution as the average noise. The evaluation of the noise is also crucial to properly set the threshold of the discriminator when digitizing the signal. Indeed, the threshold must be set to a higher value than the noise, i.e. safely above the noise distribution, to avoid fake hits. For instance, defining μ as the mean of the noise distribution and σ as its RMS, if the threshold is set to a value of $\mu + 2 \cdot \sigma$ the expected occupancy will be 0.01%.

3.4 Exposure to X -ray sources

The interaction of silicon with X -rays has been explained in Section 2.2.2.1. There are several commercially available X -ray sources. In particular, this thesis will show data taken with ^{55}Fe and ^{241}Am .

^{55}Fe is an isotope of iron that is commonly used for detector calibrations. It decays by electron capture to ^{55}Mn with a half-life of 2.7 years. The electron capture is followed by emission of a 5.9 keV X -ray [72]. The ^{241}Am source, instead, has a broader spectrum, which ends with a peak at 59.6 keV [73].

The most relevant feature that can be extracted from an X -ray spectrum is the full-absorption peak. This peak is formed when the X -ray is emitted with peak energy and all the charge released in the semiconductor bulk is collected. In this case, there are two contributions to the width of the peak: the intrinsic noise of the read-out electronics and the stochastic fluctuations on the number of electron-hole pairs released. These fluctuations are due to the fact that the electron-hole pairs are generated from several energy levels. Thus, X -rays with the same energy are not always converted in the same amount of electron-hole pairs. An example of an ^{55}Fe spectrum is shown in Figure 3.7.

The detection of the peak is a common procedure for sensor calibration. The energy of the peak can be converted to the number of released electrons (e^-) by dividing the peak energy by the ionization energy (see section 2.2.2). This way, the centre of the peak measured in “output units” can be related to the collected charge in electrons, and therefore the output of the sensor can be calibrated.

Along with the peak, there is often a flatter portion of the spectrum at lower energies. This is due to partial absorption of the X -rays, generally caused by charge sharing, charge trapping or soft X -ray escape.

3.5 Exposure to ^{90}Sr source

Since the pixel and strip detectors under investigation are prototypes for tracking systems, the tests with charged particles are crucial for their characterization. For this thesis, two sources of charged particles have been used: beta radiation sources, specifically ^{90}Sr , and particle beams.

^{90}Sr is a β^- radioactive source. It decays to ^{90}Y with a maximum electron energy of 546 keV. The ^{90}Y also decays to ^{90}Zr by emitting a beta-ray with maximum energy of 2.27 MeV [74]. The feature that makes this source interesting for detector characterization is that some of the emitted electrons have enough energy to cross a silicon layer a few hundreds of micrometers thick. One can therefore extract the MIP charge collection spectrum from

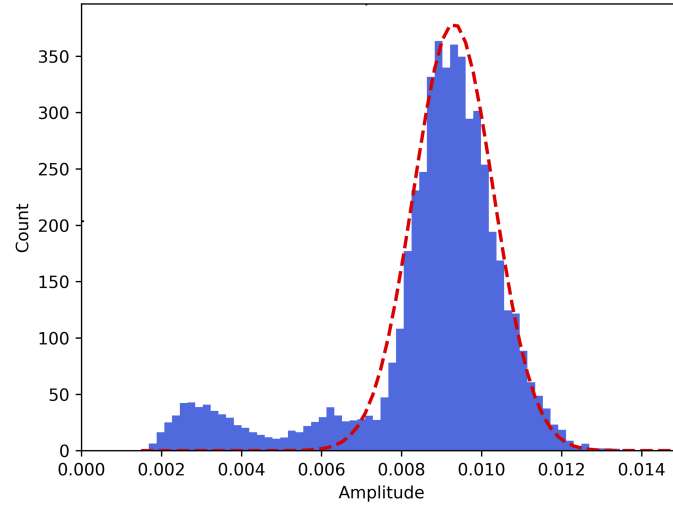


Figure 3.7: Example of an ^{55}Fe spectrum. The full-absorption peak can be noticed from the Gaussian fit, while the lower part of the distribution is rather flat with a low energy peak due to electronic noise.

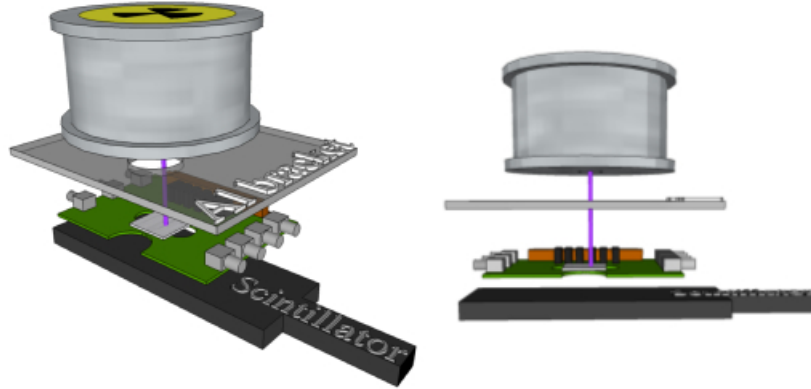


Figure 3.8: ^{90}Sr setup in the lab with a CMOS prototype device.

a silicon detector with a ^{90}Sr source [75]. The distribution of collected charge with MIPs follows a Landau function, as explained in Section 2.2.2.2.

Most of the emission spectrum, though, consists of low energy electrons. These can be fully absorbed in the silicon bulk and therefore release charge differently from MIPs. Thus, to reject these signals, a reference detector must be placed after the detector under test, and the signals of the two detectors must be recorded in coincidence. This way, one can select those electrons which cross the detector under test and then release the signal in the second detector. Generally, given their fast response and large availability, scintillators are used as reference detectors for coincidences. A schematic of the ^{90}Sr setup in the lab with a CMOS prototype device is shown in Figure 3.8.

3.6 Pixel relative efficiency with radiation sources

An interesting feature that can be computed with radiation sources is the pixel relative efficiency. To do this, one must compare the hit rate pixel by pixel. The observed rate on pixel i , for instance, will be given by

$$r_i = R \cdot e_i \cdot g_i \quad (3.2)$$

where R is the radioactive source rate, e_i is the efficiency of the pixel and g_i is a geometric factor which accounts for the solid angle between the source surface and the pixel itself. To calculate the absolute efficiency, one should compute the geometric factor g_i for every pixel. The calculation of this factor, though, is quite difficult. Its value depends on the position of the pixel with respect to the source, which is complicated to measure with high precision. Nevertheless, if the source surface is very large compared to the chip surface, this factor can be considered equal for all the pixels. Thus the ratio between the rates of two pixels corresponds to the ratio between their efficiencies. Considering a matrix of pixels, therefore, one can define the highest efficiency pixel as the one with the highest rate, r_{max} , and then compute the relative efficiency of every pixel i with respect to it as

$$e_{i,rel} = \frac{r_i}{r_{max}} \quad (3.3)$$

The source rate on the pixel can be measured experimentally by plotting the distribution of time difference between successive pixel hits. This argument can be explained as follows. The value of the time difference distribution at a certain time t is proportional to the probability that a decay happens at time t . To compute this probability, we divide the time t in an arbitrary number of time intervals Δt_j with $j = 1, \dots, J$. At each fraction of time Δt_j the decay probability over time, λ , is constant. Considering a source of N radioactive atoms, at each instant Δt_j , the probability that an atom decays is $N\lambda\Delta t_j$. On the other hand, the probability in a given time interval that no atoms decay is then $1 - N\lambda\Delta t_j$. In this case, $N\lambda$ is also the source rate, R , of equation 3.2. If we consider the response of a single pixel, we must substitute $N\lambda$ with r_i .

The probability that any of the N atoms, starting at a given time $t = 0$, decays at time t is then the probability that it does not decay up to the $(J - 1)_{th}$ interval, and then decays at the J_{th} interval. Given that the decay probability at each interval is independent of the previous intervals, the total probability is the product of the probabilities of the single time intervals:

$$p(t)\Delta t_J = \prod_{j=1}^{J-1} (1 - r_i\Delta t_j) \cdot r_i\Delta t_J \quad (3.4)$$

Since all the quantities are positive, we can apply the logarithmic function to both sides:

$$\log(p(t)\Delta t_J) = \log\left(\prod_{j=1}^{J-1} (1 - r_i\Delta t_j) \cdot r_i\Delta t_J\right) . \quad (3.5)$$

We recall here that the logarithm of a product of elements is the sum of the logarithms of the single elements and that $\log(1 + \epsilon) \sim \epsilon$ for small ϵ . The equation then becomes:

$$\log(p(t)\Delta t_J) = \sum_{j=1}^{J-1} \log(1 - r_i\Delta t_j) + \log(r_i\Delta t_J) \sim \sum_{j=1}^{J-1} (-r_i\Delta t_j) + \log(r_i\Delta t_J) \quad (3.6)$$

where we consider Δt_j to be very small. Now we can consider Δt_j to be infinitesimal, and the sum will become an integral:

$$\log(p(t)dt) \xrightarrow{\Delta t_j \rightarrow dt} \int_0^t (-r_i dt) + \log(r_i dt) = -r_i t + \log(r_i dt) . \quad (3.7)$$

Inverting now the formula for $p(t)$:

$$p(t)dt = r_i e^{-r_i t} dt \quad (3.8)$$

which is the probability density function describing the time difference distribution. As a probability density function, this distribution is correctly normalized:

$$\int_0^\infty p(t)dt = 1 \quad (3.9)$$

and the mean time τ is given by:

$$\tau = \int_0^\infty t \cdot p(t)dt = \frac{1}{r_i} . \quad (3.10)$$

This is known as the Marsden-Barratt law [76].

Given this relation, we can measure r_i from the exponential coefficient of the time-difference distribution, and then, following Equation 3.3, we can compute the pixel relative efficiency. This method for the computation of pixel relative efficiency is very convenient, since one can verify the uniformity in performance of a detector in a simple way.

3.7 Test beam

A test beam is one of the most powerful methods to evaluate the performance of detectors. Within this category of tests are included a series of studies performed with high energy particle beams using telescopes for track reconstruction. Typically, the particles used in test beams are electrons or protons with energy ranging from a few to more than a hundred GeV. Generally, tracking telescopes consist of a series of pixel detectors, named telescope planes,

with the Detector Under Test (DUT) inserted in the middle. This way, when a particle crosses all the telescope planes and the DUT, the track can be reconstructed from the hits recorded by the telescope planes. In this process, the telescope planes must be aligned, i.e. their relative position and rotation must be computed with accuracy. The alignment procedure is explained below.

Once the telescope planes are aligned and the tracks reconstructed, the particle hit positions onto the DUT can be extrapolated from the intersection of the reconstructed tracks with the DUT plane. This information, then, can be associated with the hits recorded by the DUT and used for several important studies. The relevant features that can be investigated in a test beam are the resolution, efficiency and the charge collection of the DUT.

Alignment

When taking data with the telescope, each plane records the hits in its local reference frame. For ease of reference, we set the z axis to be parallel to the beam axis, x to be the horizontal coordinate and y the vertical coordinate. The hit position in each plane's reference system will be then

$$\mathbf{x}' = (x_{meas}, y_{meas}, 0) \quad (3.11)$$

where x_{meas} and y_{meas} are the measured x - y positions on the plane.

Common to all planes there is a global reference system, where the hits from the different planes can be related to each other. For every plane, then, there is a coordinate transformation to move from the local to the global reference system:

$$\mathbf{x} = \mathbf{R}_{tot} \cdot (\mathbf{x}' - \mathbf{x}'_0) \quad (3.12)$$

where

$$\mathbf{x}'_0 = (x'_0, y'_0, z'_0) \quad (3.13)$$

is a three-dimensional translation parameter, while $\mathbf{R}_{tot}$ is a rotation matrix defined from its inverse:

$$\mathbf{R}_{tot}^{-1} = \mathbf{R}_z(\gamma) \cdot \mathbf{R}_y(\beta) \cdot \mathbf{R}_x(\alpha) \quad (3.14)$$

In this definition $\mathbf{R}_z$, $\mathbf{R}_y$ and $\mathbf{R}_x$ are the rotation matrices around the z , y and x axes respectively, while γ , β and α are the relative rotation angles. The extended definition of $\mathbf{R}_{tot}$ is then

$$\begin{bmatrix} \cos(\beta)\cos(\gamma) & \cos(\beta)\sin(\gamma) & -\sin(\beta) \\ -\cos(\alpha)\sin(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) & \cos(\alpha)\cos(\gamma) + \sin(\alpha)\sin(\beta)\sin(\gamma) & \cos(\beta)\sin(\alpha) \\ \cos(\alpha)\sin(\beta)\cos(\gamma) + \sin(\alpha)\sin(\gamma) & \cos(\alpha)\sin(\beta)\sin(\gamma) - \sin(\alpha)\cos(\gamma) & \cos(\alpha)\cos(\beta) \end{bmatrix} \quad (3.15)$$

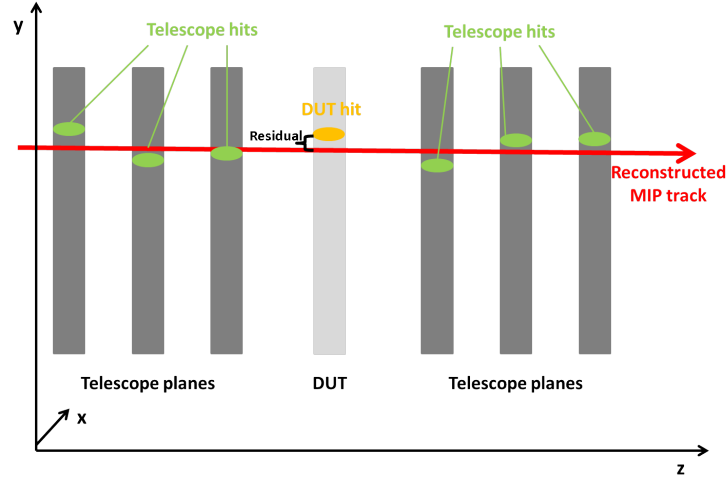


Figure 3.9: Sketch of a telescope system. The DUT is in the middle of the telescope planes.

Initially, tracks are reconstructed with the planes’ nominal positions. Afterwards, the residuals are computed. For each plane, the residuals are defined as the difference between the positions measured by the plane and the positions obtained from the interpolation of the tracks with the plane itself. If that specific plane is used in the track reconstruction, the residuals are called “constrained” residuals, otherwise they are called “unconstrained” residuals. A sketch of a telescope system with the DUT can be found in Figure 3.9.

Since the tracking algorithm uses the hit positions in the global reference system, it is crucial to know the translation and rotation parameters for each plane with high accuracy. The alignment is the procedure to compute these parameters.

The alignment procedure used in this thesis has been implemented in the *testbeam_analysis* software package [77], and is based on corrections on the residual distributions. In the case of an accurately aligned telescope each plane’s residuals form Gaussian distributions centred about 0 for both x and y coordinates, independently of the hit positions on the plane, with the RMS equal to the resolution. A misalignment in the translation parameters will shift the centre of the residual distributions. The first step of the alignment algorithm, therefore, is to perform a Gaussian fit to the x and y unconstrained residual distributions in the global reference system, and then set the x'_0 and y'_0 parameters to the obtained Gaussian mean values. An example of residual distributions before alignment can be found in Figure 3.10. The second step of the alignment algorithm is aimed to compute the rotation angles. These can be derived for every telescope plane from the correlation between unconstrained residuals and hit positions as follows. A bi-dimensional histogram is plotted for every combination of residual and hit position coordinate. Since there are two measured coordinates, there is a total of four combinations. If the planes are not rotated with respect to any axis then these histograms will not show any correlation. If instead some rotation angles are applied, the mean of the residual distribution will shift linearly with the hit position, leading to a

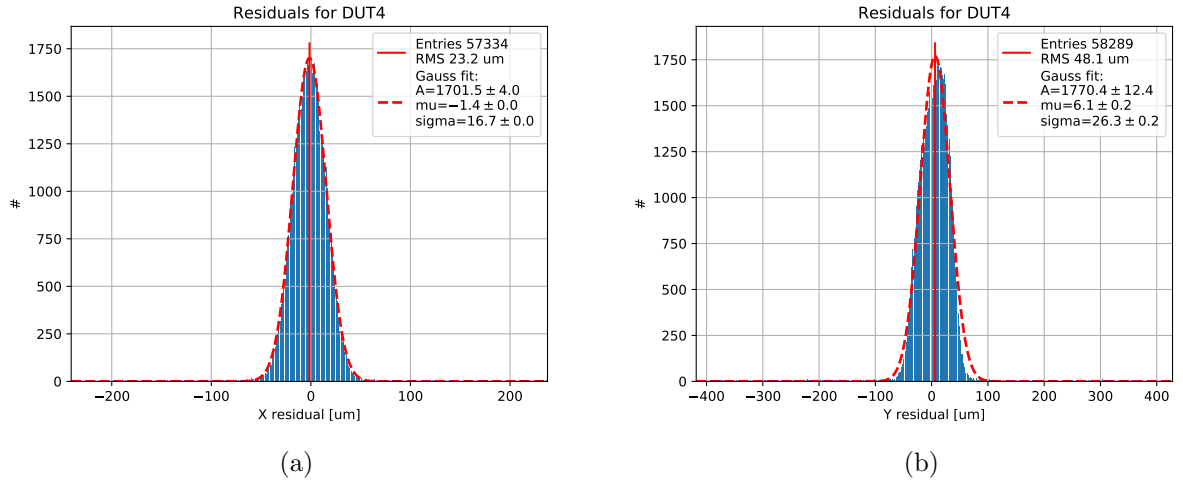


Figure 3.10: Examples of residual distributions for (a) x and (b) y coordinates before alignment.

non-zero correlation (see Figure 3.11). For instance, if an angle γ is applied around the z axis, the reconstructed x position will shift away from the measured one as the track moves along the y coordinate. A sketch representing this effect can be found in Figure 3.12.

More specifically, in this step of the alignment procedure, the centre of the residual distribution is computed in every bin for each of the four bi-dimensional residual-position distributions. The obtained curve is then fitted with a straight line. For ease of reference, the four slope parameters obtained from the fit are named m_{xx} , m_{xy} , m_{yx} and m_{yy} , where the first letter refers to the residual coordinate and the second to the hit position coordinate. These parameters are related to the difference between the positions in the two local reference systems, i.e. $\mathbf{x} - \mathbf{x}' = (\mathbf{R}_{tot} - \mathbf{1}) \cdot (\mathbf{x}' - \mathbf{x}'_0)$. The four slopes, therefore, are equal to the four x - y elements of the $(\mathbf{R}_{tot} - \mathbf{1})$ matrix. Using the definition of $\mathbf{R}_{tot}$ in 3.15, a set of four equations in three variables is obtained:

$$\begin{cases} m_{xx} = \cos(\beta)\cos(\gamma) - 1 \\ m_{xy} = \cos(\beta)\sin(\gamma) \\ m_{yx} = -\cos(\alpha)\sin(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) \\ m_{yy} = \cos(\alpha)\cos(\gamma) + \sin(\alpha)\sin(\beta)\sin(\gamma) - 1 \end{cases} \quad (3.16)$$

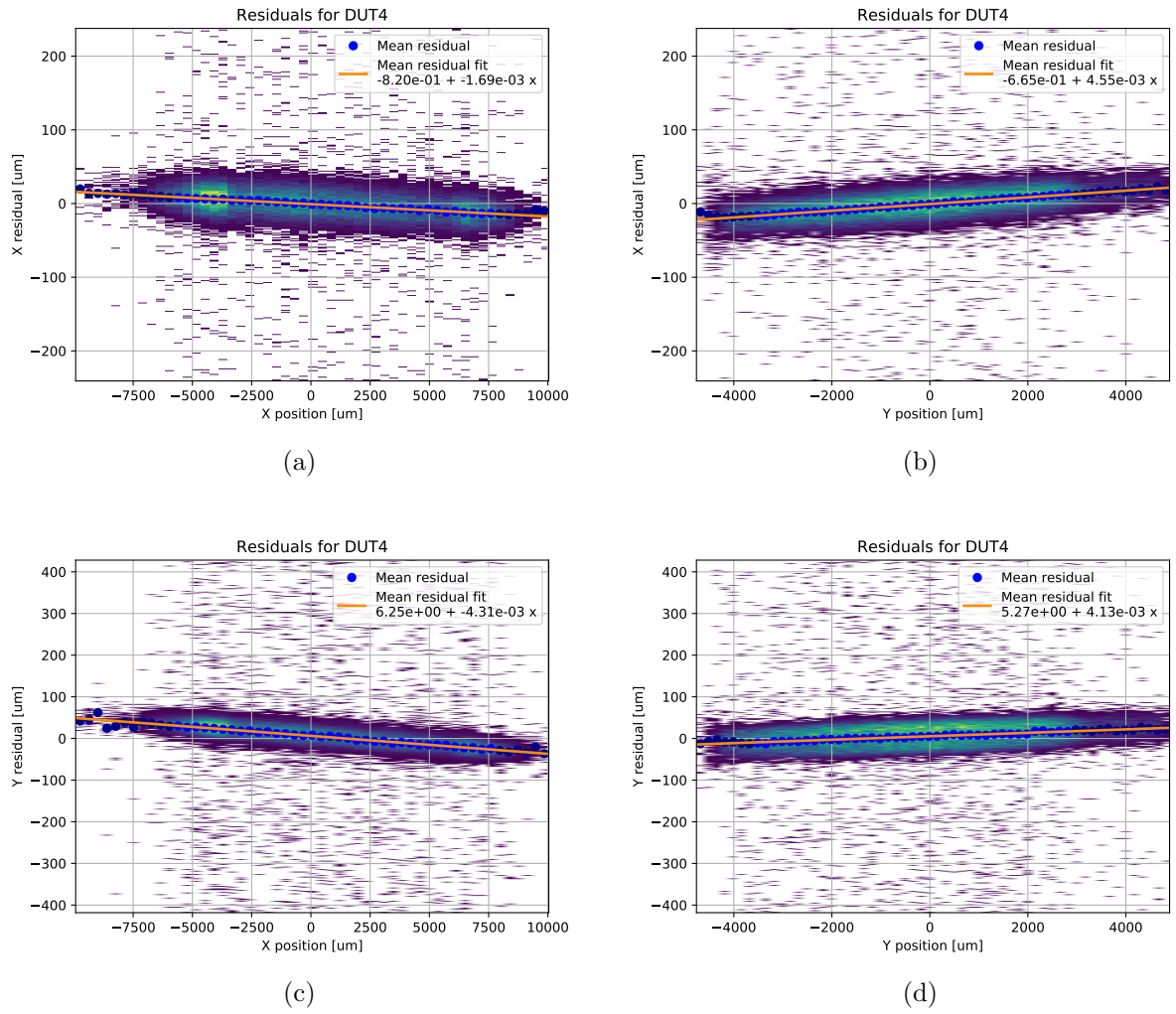


Figure 3.11: Examples of bi-dimensional distributions of residuals against hit position before alignment: (a) x residuals vs x position, (b) x residuals vs y position, (c) y residuals vs x position, (d) y residuals vs y position.

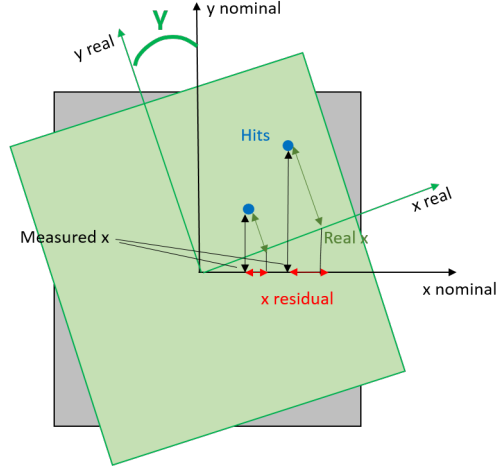


Figure 3.12: The effect of a rotation around the z axis on the position reconstruction. The nominal reference system is the one used in track reconstruction (grey), while the real reference system is rotated by an angle γ (green). In such a case, it can be seen that the x residual increases with increasing hit position on the y axis.

The solution of this system of equations is

$$\left\{ \begin{array}{l} \tan(\gamma) = \frac{m_{xy}}{1+m_{xx}} \\ \cos(\beta) = \frac{1+m_{xx}}{\cos(\gamma)} \\ \cos(\alpha) = \frac{m_{yy}-\tan(\gamma)m_{yx}+1}{\cos(\gamma)+\sin(\gamma)\tan(\gamma)} \\ \frac{m_{xy}}{1+m_{xx}} = \frac{m_{yx}-\sin(\alpha)\sin(\beta)\cos(\gamma)}{1+m_{yy}-\sin(\alpha)\sin(\beta)\sin(\gamma)} \end{array} \right. \quad (3.17)$$

where the last equation is redundant and can be used to verify the first three.

After applying these corrections for all planes, the tracks are reconstructed again. The procedure then can be repeated for a certain number of cycles. Generally, two cycles are sufficient to obtain good residual distributions, i.e. centred about 0 and with negligible residual-position correlations. The effect of the alignment on the one-dimensional and bi-dimensional residual distributions can be seen in Figures 3.13 and 3.14 respectively. One can notice that the total residual distributions are now even in x and y , and the RMS is reduced by a factor of 2-3. At the same time, the correlation between residual and position is reduced by an order of magnitude.

The alignment procedure is then applied to the DUT as well. Once the alignment is finalized, the track intersections with the DUT plane can be extrapolated for the analysis.

Resolution

When a particle traverses the DUT, more than one pixel can detect a signal at the same time. In this case, the ensemble of the contiguous hit pixels is called a *cluster*. Clusters can

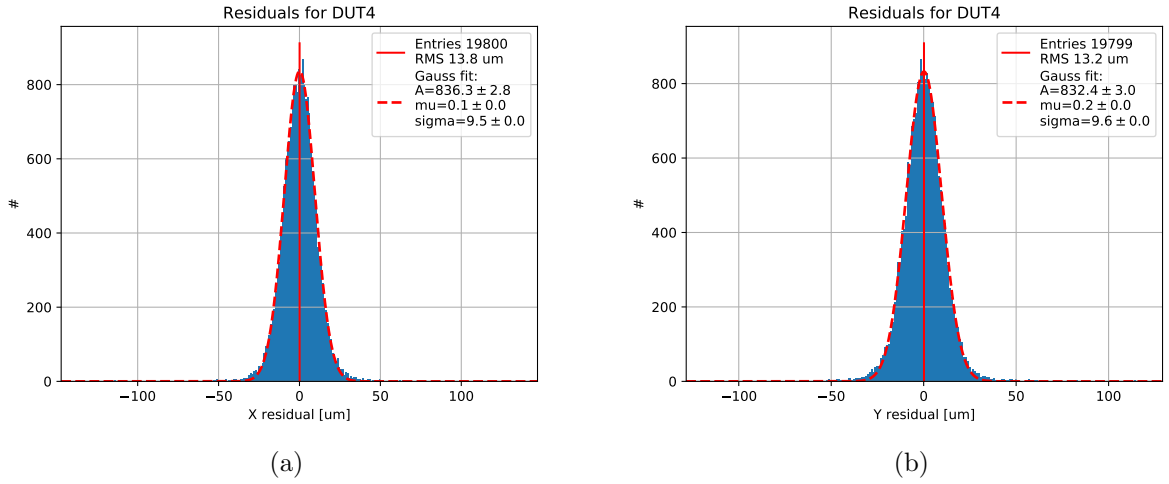


Figure 3.13: Examples of residual distributions for (a) x and (b) y coordinates after alignment.

be classified depending on their size and geometry. The cluster geometry is correlated with the hit position of the particle. For instance, in clusters of size one, the particle hit position is closer to the centre of the pixel, while in clusters of size two it is closer to the boundary between the two pixels. This can be explained with the charge sharing effect, as shown in Figure 3.15. In a test beam, therefore, if the telescope resolution is significantly smaller than the DUT's pixel pitch, one can reconstruct the spatial distribution of the hits and the residuals depending on their cluster size (an example of a size 2 cluster hit distribution is provided in Figure 3.16). Thus, from the study of these distributions, one can determine the precision with which the hits are reconstructed by the detector.

Efficiency

The efficiency is defined as the ratio between the number of particles detected by the sensor and the number of particles traversing it. In a test beam, thanks to the track reconstruction, for each particle one can predict which pixel it hits, and then check if that pixel has detected a signal. Generally, due to charge sharing and tracking resolution, the hits on the surrounding pixels are checked too. This study provides an estimation of the absolute pixel efficiency. In addition, if the telescope resolution is significantly smaller than the DUT's pixel pitch, one can relate the efficiency to the hit position inside the pixel itself. This is called in-pixel efficiency, and it can reveal eventual non-uniformities in charge collection. As an example, Figure 3.17 shows the in-pixel efficiency map for two 3D pixel detectors. In this case, the devices have collecting electrodes inserted as columns in the silicon bulk, and they appear in an in-pixel efficiency map as areas of lower efficiency.

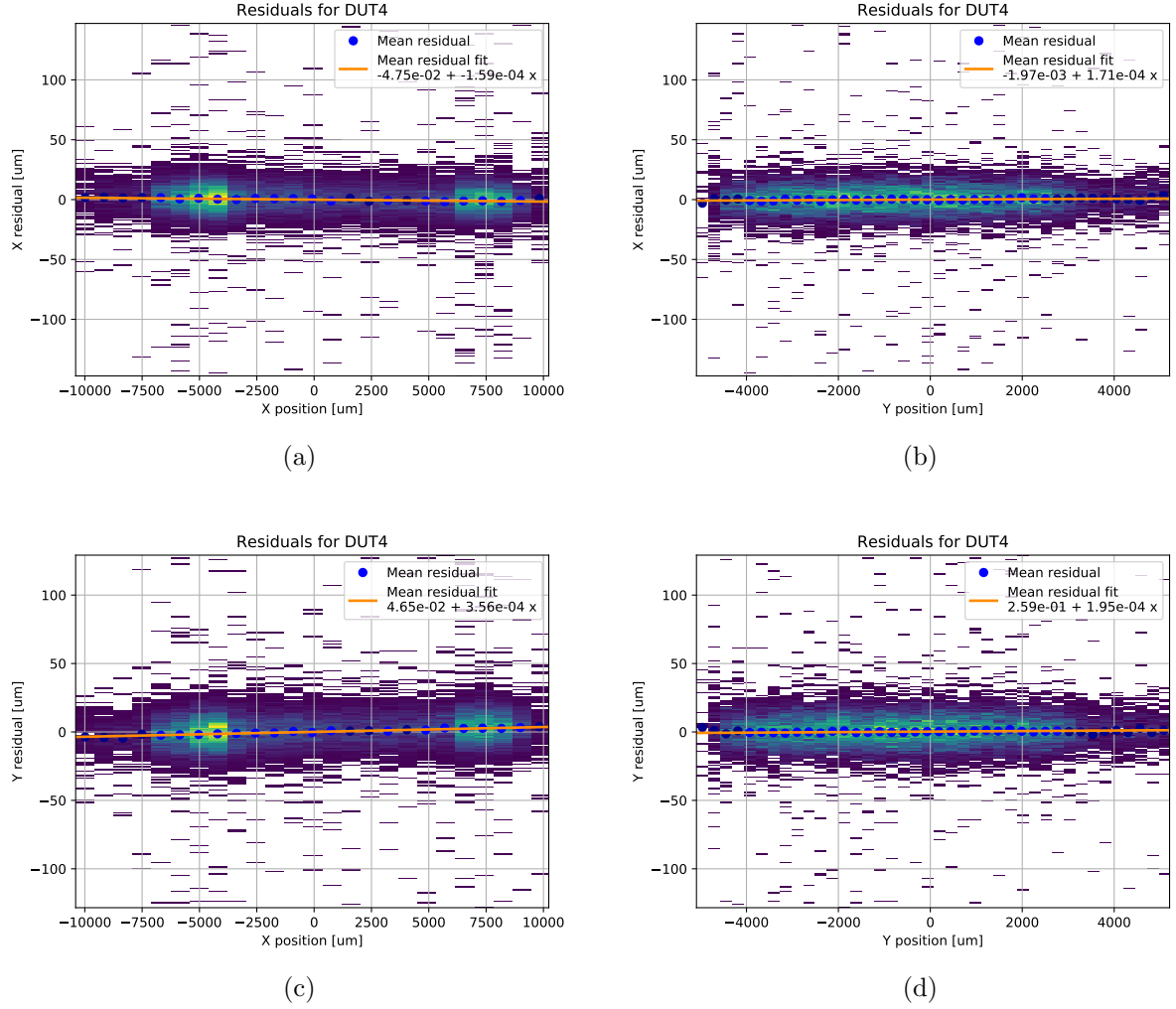


Figure 3.14: Examples of bi-dimensional distributions of residuals against hit position after alignment: (a) x residuals vs x position, (b) x residuals vs y position, (c) y residuals vs x position, (d) y residuals vs y position.

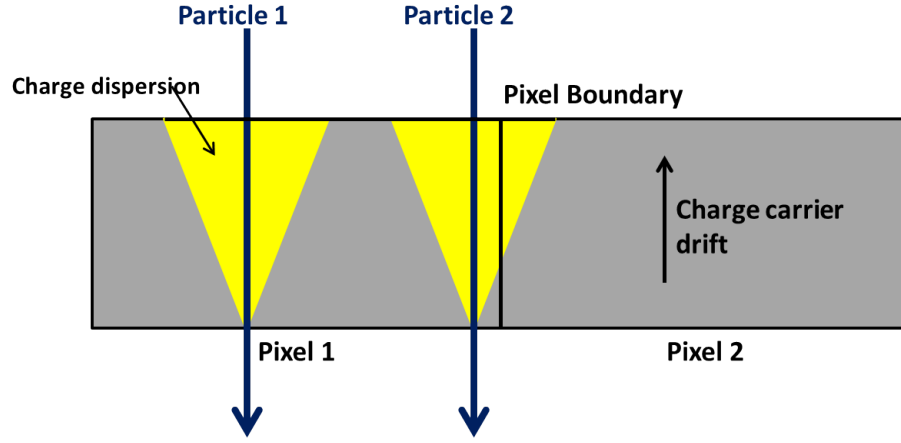


Figure 3.15: Schematics of cluster formation. Particle 1 hits pixel 1 close to the centre, the charge dispersion is confined in the pixel. The cluster size in this case is then 1. Particle 2 hits pixel 1 close to the boundary with pixel 2, and the part of the charge reaches pixel 2. The cluster size in this case is then 2.

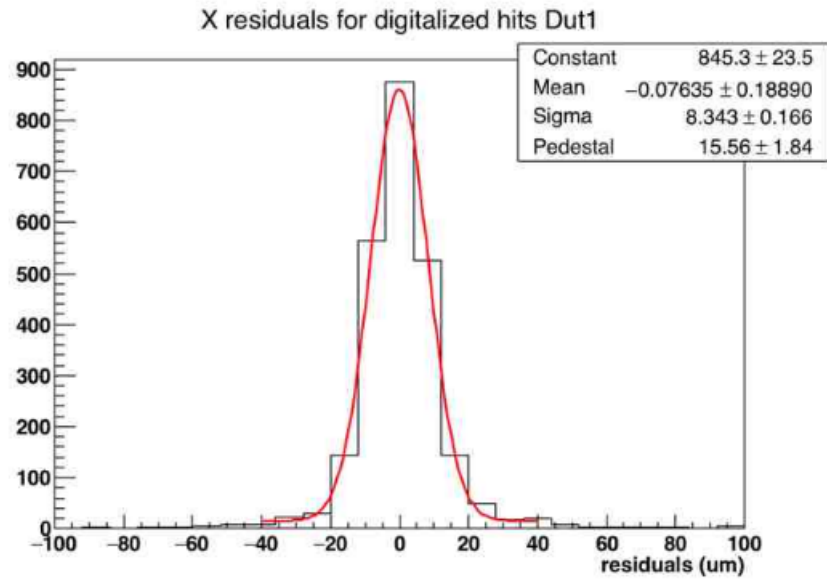


Figure 3.16: Distribution of size 2 cluster hits for a 3D silicon detector using the Fermilab test beam facility's telescope [78].

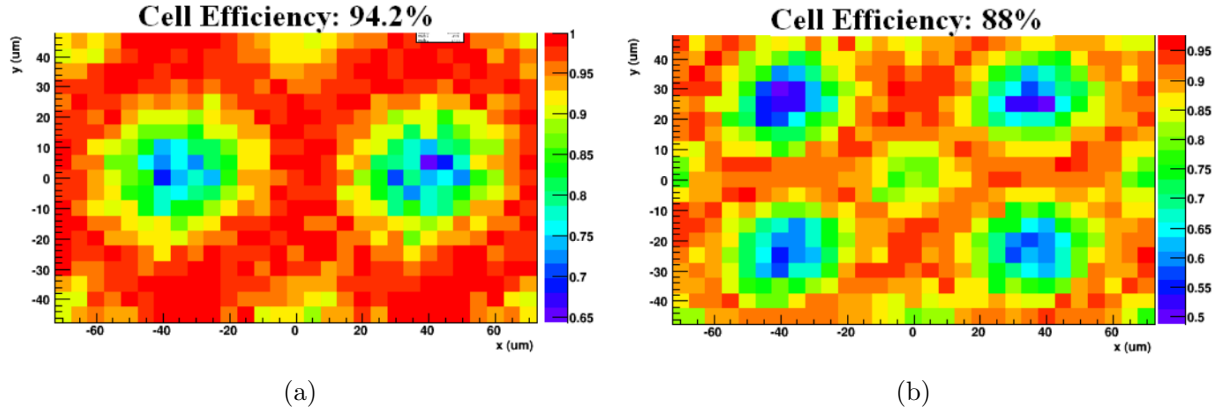


Figure 3.17: Examples of in-pixel efficiency maps for 3D silicon detectors [79]. In these detectors the electrodes are inserted in the silicon bulk in column-like structures and are seen as areas of reduced efficiency. In particular, (a) shows a prototype with 2 collecting electrodes and (b) with 4.

Charge Collection

If the telescope resolution is significantly inferior to the DUT's pixel pitch, one can calculate the average collected charge as a function of the hit position. This can be done only if the DUT's read-out system provides information about the collected charge. Typically, a sensor is considered to have good performance if the charge collection profile is uniform inside the pixel. Some charge loss generally appears at the boundary of the pixel because of charge sharing (see Section 2.3.2). In this case, the pixel may belong to a cluster, and therefore one can aggregate the charge of all the pixels in the cluster.

Facilities

There are several facilities which provide access to test beams. The work shown in this thesis features test beam activities carried out in two facilities: ELSA (Bonn) and DESY (Hamburg).

ELSA (Electron Stretcher Accelerator) is a test beam facility based at the University of Bonn, Germany [80]. It provides users with a 3 GeV electron beam.

The DESY laboratory in Hamburg (Germany) also features a test beam facility [81]. Users in this case can take advantage of an electron beam with energies ranging from 1 to 6 GeV. The facility consists of three beam-lines, two of which are provided with a MIMOSA26 telescope for track reconstruction. The resolution of such a telescope can be as low as $3.24 \mu\text{m}$ [65].

3.8 Time-walk measurements

In many silicon detectors, the pulse generated by the preamplifier reaches threshold at a time which depends on the height of the pulse. This feature is called time-walk (see Section 2.3.1.2). Since the bunch crossing time of the LHC is 25 ns, it is crucial that all the pulses in the signal spectrum cross the threshold within 25 ns, otherwise some hits may be wrongly associated with another bunch. In other words, since the threshold crossing time is inversely proportional to the pulse height, the higher is the height of the pulse, the faster it will cross the threshold. The requirement imposed by the LHC on ATLAS is that the dispersion in threshold crossing time between the highest and the lowest pulse is less than 25 ns. The fraction of pulses whose threshold crossing time is within 25 ns is called the in-time efficiency. To measure the time-walk experimentally, a charge signal must be sent to the read-out circuitry and the threshold crossing time must be recorded with respect to the time of the signal production. The charge signal can be delivered in different ways, such as particle beams, injection, or via a laser. The difference between threshold crossing time and signal time is then plotted in a bi-dimensional plot against the pulse height. From this plot, one can estimate how many pulses lie within 25 ns of the earliest pulse.

More specifically, whilst the threshold crossing time is registered by the read-out, the measurement of the signal time depends on the way the signal is produced. For instance, in a test beam a scintillator (or more scintillators in coincidence) can be used to produce a time-reference signal. If the signal is sent through injection, the injection circuit can send out a time-reference signal. The laser system used in the OPMD sends a fast trigger signal which can be used for the time reference of the charge production.

Chapter 4

Characterization of CMOS devices

This chapter will show the work performed on three different projects, related to three different implementations of the CMOS technology in High Energy Particle Physics:

- CMOS active and monolithic pixel sensors
- CMOS passive pixel sensors
- CMOS strip detectors.

In each of these projects prototypes have been developed to verify and test the feasibility of the CMOS technology for the upgrade of the ATLAS experiment. This chapter, therefore, consists of three sections, each dedicated to one of the three projects. Each section provides a description of the prototypes that have been studied and shows the results thus collected.

4.1 CMOS active and monolithic pixel sensors

Within the ATLAS CMOS Pixel collaboration, one of the most important projects is the one leading to the production of a fully monolithic device with LFoundry technology [82]. This foundry provides both high resistivity wafers (typically 3-5 k Ω ·cm, with a minimum of 2 k Ω ·cm) and high bias add-ons for the design of CMOS devices. These features include multiple well structures with different doping levels to protect the electronics.

This thesis will cover three different types of LFoundry devices:

- CCPD.LF, an active device where the initial stage of the signal processing is implemented [83].
- LF-CPIX, a larger and more advanced active device than CCPD.LF.

- LF-MONOPIX, the first fully monolithic device produced with this technology [84].

The first two prototypes, CCPD-LF and LF-CPIX, are very similar in many aspects. Both of them are fabricated in LFoundry 150 nm technology, which is based on a p-substrate with the charge collected through an n-type electrode (see Figure 4.1(a)) [85]. In this process, a sequence of wells of different doping levels guarantees protection from high voltage to the electronics. In both devices a preamplifier, feedback resistance, source follower, baseline adjustment and comparator are implemented inside each pixel. The schematic of this basic read-out is sketched in Figure 4.1(b). In particular, the preamplifier can have different “flavours”, depending on the type of input transistor: NMOS, PMOS or CMOS (the CMOS preamplifier is implemented in LF-CPIX only).

Both prototypes can be read-out in two ways. One way is to transmit the preamplifier and comparator output of one pixel through a stand-alone board to an oscilloscope. The second way is to capacitively glue the whole device to a front-end chip, the recommended one being FE-I4. All the devices used in this chapter have not been thinned, therefore their thickness is the LFoundry 725 μm standard thickness. All the LFoundry devices used in this chapter have been read with the stand-alone board as in Figure 4.1(b), and therefore their analogue output has been analyzed.

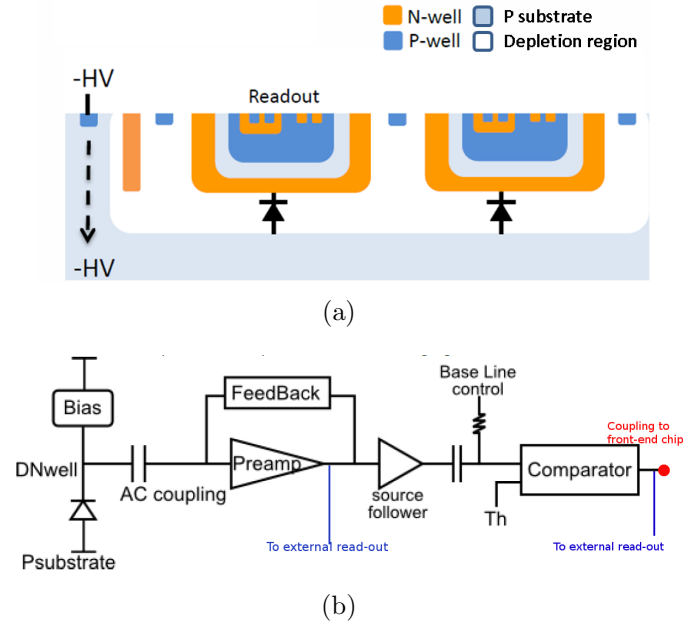


Figure 4.1: (a) Side view of the LFoundry process. (b) Single pixel cell schematics for the active CMOS sensors. One can read-out the preamplifier and comparator with a stand-alone board or glue it with capacitive glue to a front end chip.

There are some differences between the two prototypes, which will be described in the following paragraphs.

4.1.1 CCPD_LF

4.1.1.1 Description

The first prototype produced with LFoundry technology is CCPD_LF [85]. This device has been designed with a pixel size of $125 \times 33 \mu\text{m}^2$. Since the pixels of the FE-I4 chip have a size of $250 \times 50 \mu\text{m}^2$, 6 CCPD_LF pixels can be read through 2 FE-I4 pixels, with a geometric configuration of triple-column and double row.

By design, there are two variants of this prototype: Version A and B. In Version A, the read-out circuitry is surrounded by the deep n-well collection electrode isolating the read-out circuitry from the p-substrate. A negative bias voltage can be applied to the p-substrate to form the depletion region (see Figure 4.2(a)). The large collection electrode's area, though, affects the input capacitance of the read-out circuitry and induces larger read-out noise and slower response of the pixel's charge sensitive amplifier (CSA), as shown in Section 2.3.1.1. In Version B the read-out circuitry is outside the n-well leading to a small input capacitance. In this case the read-out circuitry is not isolated from the substrate. Therefore, a high bias voltage cannot be applied to the p-type substrate because it is shorted to the p-well of the read-out circuitry. The voltage level of the p-well of the read-out circuitry must be set to ground and a positive bias voltage is applied to the collection electrode (see Figure 4.2(b)). Generally, the ratio between the surface of the collection electrode and the total pixel surface is defined as the *fill factor* (see Section 2.4.3). Given this definition, CCPD_LF Version A is said to be designed with a large fill factor, while Version B with a small fill factor.

4.1.1.2 Pre-irradiation results

IV curve

First, the behaviour of the leakage current as a function of bias is investigated. This is commonly referred to as the IV curve (see Section 2.2.1.3). The IV curves for Version A and B of CCPD_LF are shown in Figures 4.3(a) and 4.3(b) respectively. These measurements were taken in a clean room at lab conditions (see Section 3.2). The behaviour of the Version A prototype is compatible with a properly reverse biased diode, with a fairly high breakdown voltage (about 120 V). The behaviour of Version B, instead, is not as good as Version A, since the leakage current increases by orders of magnitude in the application of a few Volts. For this reason, Version B prototypes have never been biased to more than 20 V.

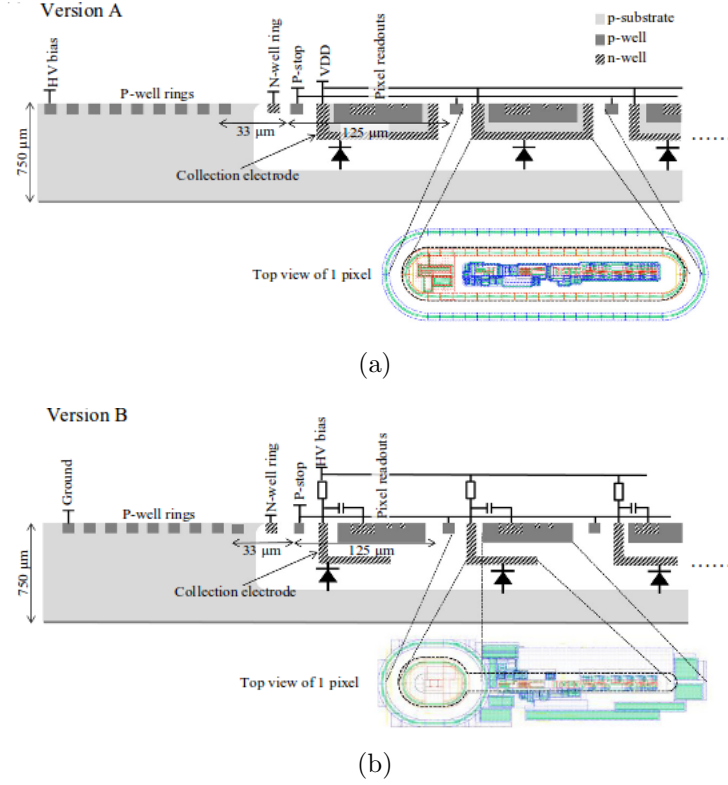


Figure 4.2: Lateral and front schematics of CCPD-LF Version (a) A and (b) B. [85]

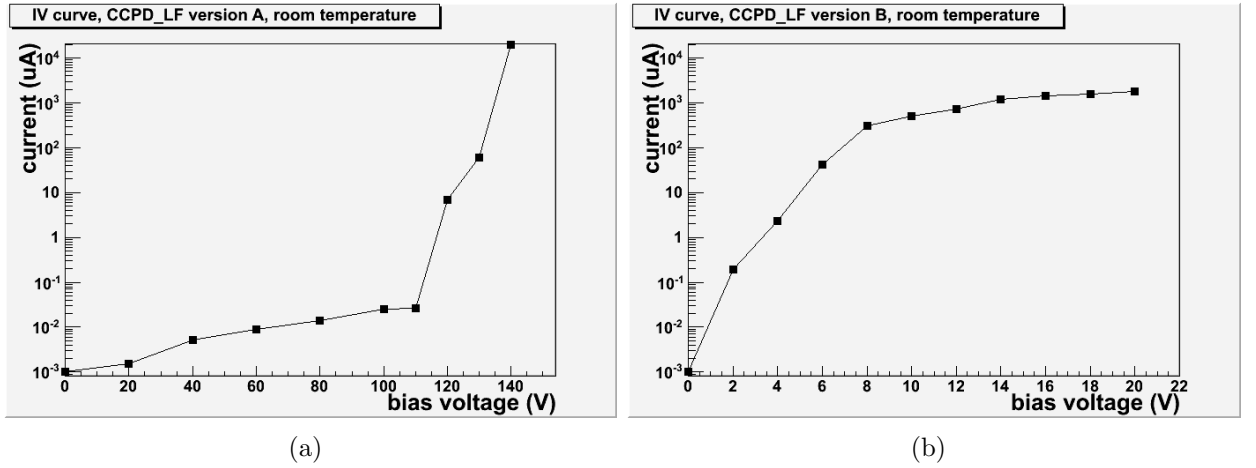


Figure 4.3: IV curves for CCPD-LF Version (a) A and (b) B.

Minimum Ionizing Particle spectrum

CCPD-LF was also tested at the ELSA facility in Bonn with a 3.2 GeV electron beam (see Figure 4.4). The distribution of collected charge is expected to follow a Landau distribution, as explained in Section 2.2.2.2. The spectra have been collected at different bias voltages and the observed distributions have been fitted with a Landau function (see Section 2.2.2.2) convoluted with a Gaussian function, which accounts for the noise. From the extracted MPV parameter the depletion depth has been computed as explained in Section 2.2.2.2.

The behaviour of the depletion depth as a function of the bias voltage has been compared with the expected behaviour for different resistivity values (see Figure 4.5), and it is shown to be compatible with a resistivity of $3 \text{ k}\Omega\cdot\text{cm}$, in agreement with the foundry's specifications [85].

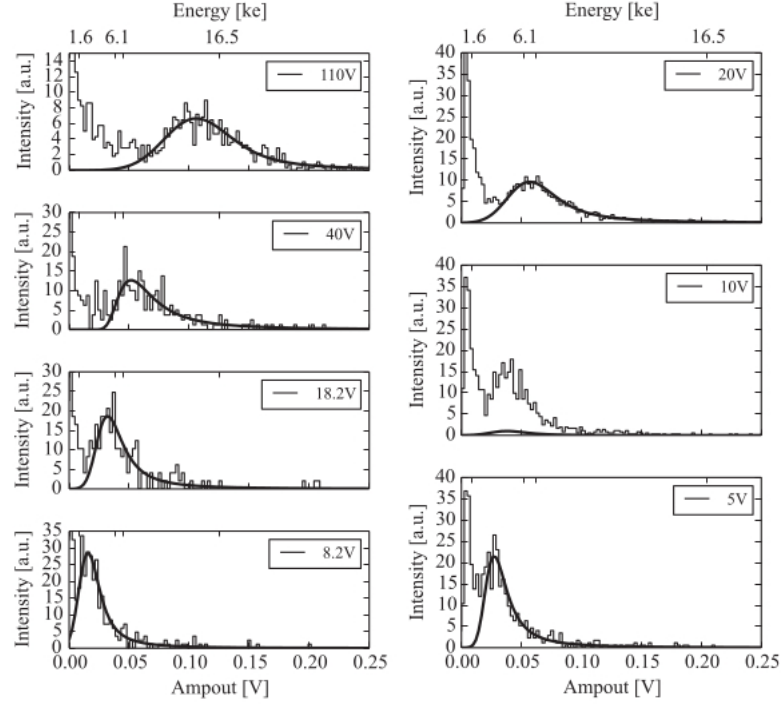


Figure 4.4: MIP spectra obtained with a 3.2 GeV electron beam with CCPD_LF Version (left) A and (right) B at different bias voltages [85]. Each spectrum has been fitted with a Landau function convoluted with a Gaussian function.

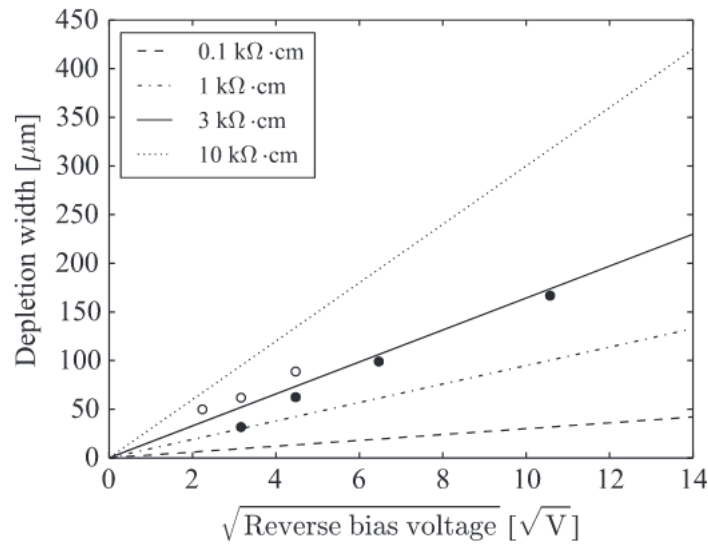


Figure 4.5: Depletion depth as a function of square root of bias for CCPD_LF version A (solid circles) and B (open circles) [85]. The lines show the dependency according to different resistivities.

Edge-TCT

The results of the test beam have been confirmed for Version A with the edge-TCT procedure. Figure 4.6(a) shows the charge profiles obtained with this method at different bias voltages. The depletion depth is then calculated as the Full Width Half Maximum (FWHM) of this distribution, and its value is computed as a function of the bias voltage (see Figure 4.6(b)). The plot of depletion depth as a function of the bias voltage has been fitted with a square root function, and the resistivity has been estimated from the fit parameters to be $3.3 \pm 0.5 \text{ k}\Omega\cdot\text{cm}$, which confirms the result obtained with the electron beam. These measurements were taken in a clean room at lab conditions (see Section 3.2).

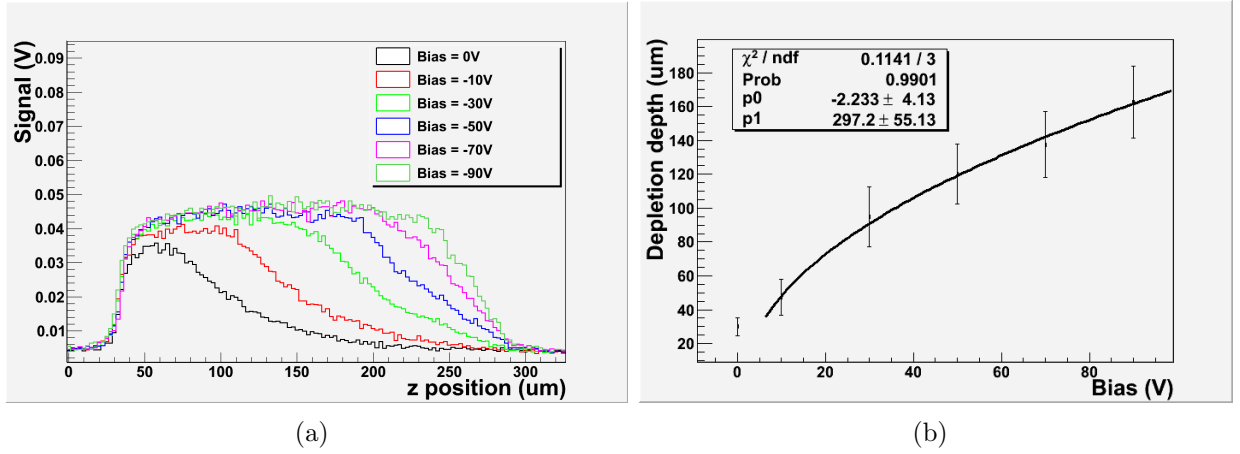


Figure 4.6: (a) Edge-TCT 1D scans of a CCPD.LF Version A active pixel. Note that the chip surface starts at about $50 \mu\text{m}$ in z -position and the depletion region extends from left to right. (b) FWHM of the signal profile versus bias.

^{55}Fe spectrum

The ^{55}Fe spectra collected with both versions of CCPD.LF (Figure 4.7) in lab conditions (see Section 3.2) show well defined full-absorption peaks. In this case, the bias voltage is 90 V for version A and 20 V for version B, and the read-out system was based on the stand-alone board (as in Figure 4.1(b)). The two plots have some differences in the lower part of the spectrum, as Version B shows a higher shoulder than Version A. This might be due to the different geometry of the deep n-well and the lower bias voltage. Given these conditions, the depletion region is smaller and therefore it has a larger surface-to-volume ratio, which may increase the effect of partial absorption.

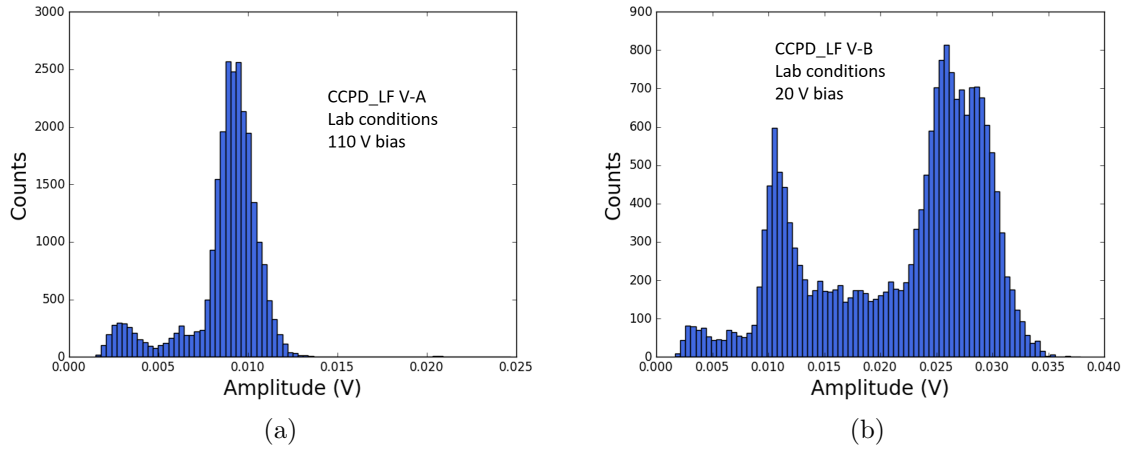


Figure 4.7: ^{55}Fe spectra obtained with CCPD_LF Version (a) A and (b) B.

4.1.1.3 Post-irradiation results

Edge-TCT

Some CCPD_LF prototypes have been irradiated at the TRIGA reactor in Ljubljana [86] with neutrons. The irradiation has been performed in steps up to a fluence of $8 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$. This fluence exceeds by far that expected for the ITk 4_{th} pixel layer, i.e. $1.5 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$. The reduction in the depletion region depth has been tested with the edge-TCT [87]. The results of this study, shown in Figure 4.8, show that even after a fluence of $2 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$ the signal-to-noise ratio remains sufficiently high, surpassing the requirements for operation in the outer pixel layers.

The results obtained with the CCPD_LF are summarized in Table 4.1.

Test	Before irradiation	After irradiation $2 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$
IV curve	Version A: 120 V breakdown Version B: no diode behaviour	Not Available
MIP spectrum	3 k Ω ·cm	Not Available
Edge-TCT	3.3 k Ω ·cm resistivity, 160 μm depletion at 90 V	50 μm depletion at 150 V
^{55}Fe	Good	Not Available

Table 4.1: Summary table of the tests performed on the CCPD_LF.

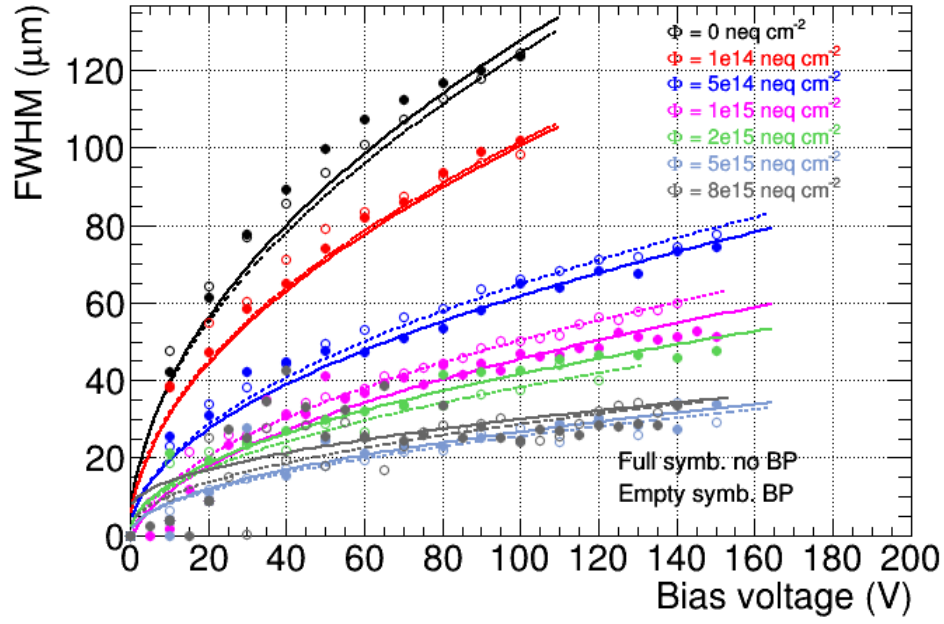


Figure 4.8: Depletion depth as a function of voltage obtained with the CCPD_LF at different irradiation doses [87].

4.1.2 LF-CPIX

4.1.2.1 Description

The second prototype produced with LFoundry technology is the LF-CPIX. This device has the same pixel size as the FE-I4 chip ($250 \times 50 \mu\text{m}^2$). When it is coupled to a front-end FE-I4 chip there is a 1:1 connection between sensor and front-end pixels. The total surface is about 1 cm^2 .

The LF-CPIX has been designed with a large fill factor strategy only. It has been produced in two versions, Version 1 and 2. The main difference between the two versions consists of the guard ring implementation, as shown in Figure 4.9. Version 2 has a reduced number of rings. Another important difference is the distance between the deep n-well and the p-well ring for each pixel, which is $4.86 \mu\text{m}$ for Version 1 and $8 \mu\text{m}$ for Version 2. The reason for this change is that the increase in the distance between the deep n-well and the p-well ring enhances significantly the breakdown voltage, as shown in the next section.

4.1.2.2 Results

In this section we will show the results of the characterization of the LF-CPIX before and after irradiation. More specifically, four LF-CPIX devices were available, two Version 1 and two Version 2. The two LF-CPIX Version 2 devices have been irradiated with 27 MeV protons to a fluence of $1.0 \times 10^{15} \text{ neq cm}^{-2}$ (about 60 % of the expected fluence on the 4_{th} layer

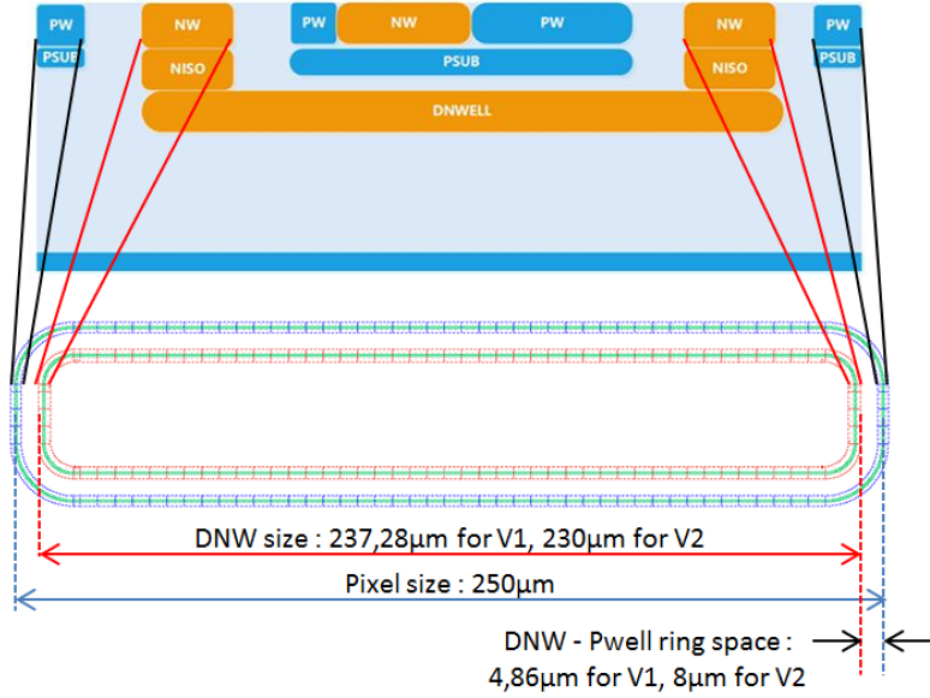


Figure 4.9: Lateral schematics of the LF-CPIX. The differences between the two versions are outlined.

of the ITk) at the Birmingham MC40 Cyclotron [88]. For every study the results before and after irradiation will then be compared.

IV curves

First, the behaviour of the leakage current as a function of bias voltage has been investigated at lab conditions (see Section 3.2). The result for both Version 1 and 2 are reported in Figure 4.10(a). The increase in the distance between the deep n-well and the p-well ring improves the breakdown voltage significantly from Version 1 (about 140 V) to Version 2 (about 210 V).

After irradiation, the leakage current was tested at -40 °C and the resulting IV curve is shown in Figure 4.10(b). Equation 2.21 predicts the increase of leakage current at 20 °C as

$$\Delta I = \Delta J \cdot V = \Delta J \cdot A \cdot d = \alpha \cdot \phi \cdot A \cdot d \quad (4.1)$$

where ΔJ is the increase in volume current, V is the volume of the depleted region, A is the surface area of the depletion region, d is the thickness of the depletion region, α is the *reverse current damage factor*, which is in the range $4\text{-}6 \cdot 10^{-17}$ A/cm at 20 °C [57], and ϕ is the fluence. Considering the surface area as 1 cm² and the depletion region thickness as 70 μm at 140 V bias (as shown later), the expected leakage current at 20 °C is then 2.8-4.2 mA. To compute the expected leakage current at -40 °C we use Equation 2.17, which defines the

behaviour of the leakage current as a function of temperature. According to this equation, the ratio between the leakage current values at the two temperatures is

$$\frac{I_{-40C}}{I_{20C}} = \frac{233^2}{293^2} \cdot \exp\left(-\frac{0.62}{8.61 \cdot 10^{-5}} \cdot \left(\frac{1}{233} - \frac{1}{293}\right)\right) = 1.15 \cdot 10^{-3} \quad (4.2)$$

Thus the expected leakage current at -40°C is $0.32\text{--}0.48 \mu\text{A}$, which is in agreement with the data in Figure 4.10(b).

Furthermore, no clear breakdown is visible at 210 V bias after an irradiation dose of $1.0 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$.

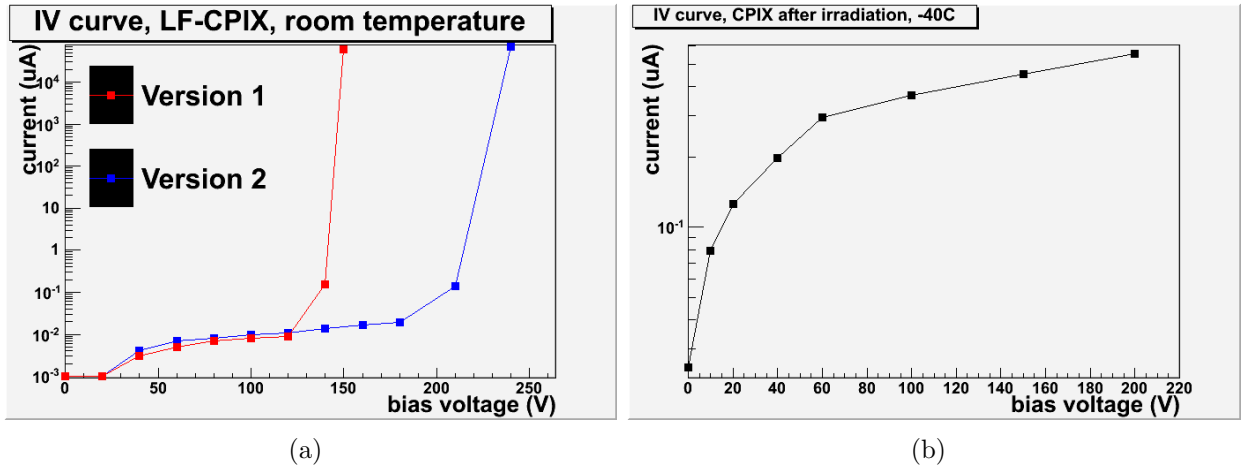


Figure 4.10: (a) IV curve for the LF-CPIX Version 1 and 2. (b) IV curve for a LF-CPIX prototype Version 2 after irradiation to $1.0 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$

Gain and noise

Proton irradiation produces damage to the electronics, known as Total Ionization Dose (TID), which may affect the gain and noise of the preamplifier [89]. The exposure to 27 MeV protons up to a fluence of $1.0 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$ corresponds to 123 Mrad of TID. The resistance of the electronics to this effect has been tested with charge injection for all the three preamplifier flavours. The measurements before irradiation were taken in a clean room at lab conditions (see Section 3.2), while after irradiation at -40°C . The results of this procedure for the three preamplifier flavours before and after irradiation is reported in Figure 4.11. These plots show that the gain is slightly affected by such an amount of TID, with a decrease of about 10% for all the preamplifier flavours.

The noise is calculated from the fluctuations above the output baseline. The fluctuation distributions for the three preamplifier flavours before and after irradiation are shown in Figure 4.12. These results show that after irradiation the noise seems to increase significantly and differently for the three preamplifier flavours. More specifically, the noise increases by a factor of 34% for the NMOS, 40% for the PMOS and 50% for the CMOS preamplifier flavour.

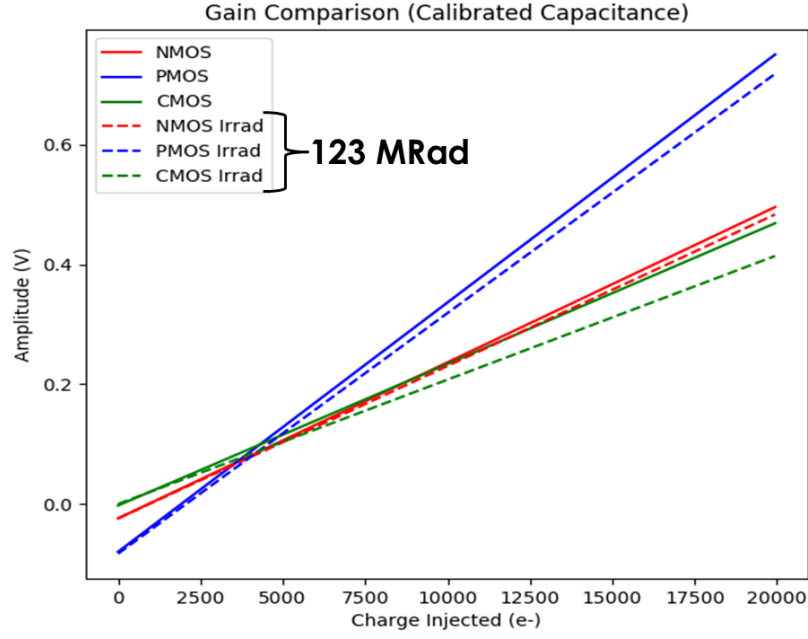


Figure 4.11: Gain curves of LF-CPIX before (solid line) and after (dashed line) irradiation for the three preamplifier flavours: NMOS (red), PMOS (blue) and CMOS (green).

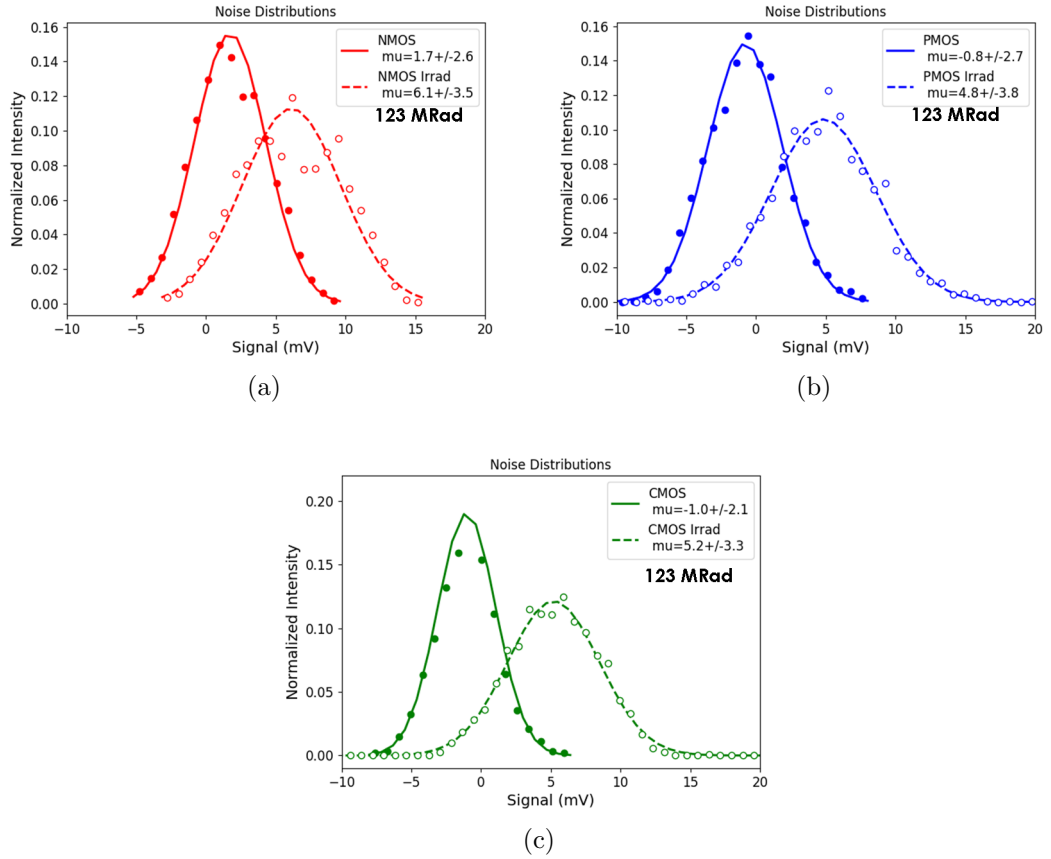


Figure 4.12: Noise distributions of the LF-CPIX before (solid line) and after (dashed line) irradiation for the three preamplifier flavours: (a) NMOS, (b) PMOS and (c) CMOS.

Given these results, we can summarize the noise using two different metrics. One is the noise as the fluctuations over the mean value, i.e. the RMS of the noise distributions. The second is to calculate the minimum threshold one has to set on the output in order to avoid noise hits. In this case, the value of the minimum threshold is calculated as

$$Thr_{min} = \mu + 2 \cdot \sigma \quad (4.3)$$

where μ is the mean value of the noise distribution and σ is its RMS. A factor of 2 is used to safely set the threshold above the noise. This way one can expect less than 0.01 % noise occupancy.

The values of noise and minimum threshold for the three preamplifier flavours are reported in Table 4.2.

Preamplifier flavour	Before irradiation		After irradiation $1.0 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$ - 123 MRad	
	Noise (e^-)	Thr_{min} (e^-)	Noise (e^-)	Thr_{min} (e^-)
NMOS	108	286	150	564
PMOS	70	160	97	315
CMOS	96	238	158	566

Table 4.2: Summary table of the noise and minimum threshold for the LF-CPIX before and after irradiation ($1.0 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$).

⁵⁵Fe spectrum

LF-CPIX Version 2 samples were exposed to X-rays with a ⁵⁵Fe source. The measurements before irradiation were taken in a clean room at lab conditions (see Section 3.2), and after irradiation at -40°C . The spectra obtained from the preamplifier output of a single pixel before and after irradiation can be found in Figures 4.13(a) and 4.13(b) respectively. These plots show the expected peak at $1640 e^-$. The RMS of the peak is $50 e^-$ before irradiation, and then increases to $73 e^-$ after irradiation, which is expected given the increase in noise.

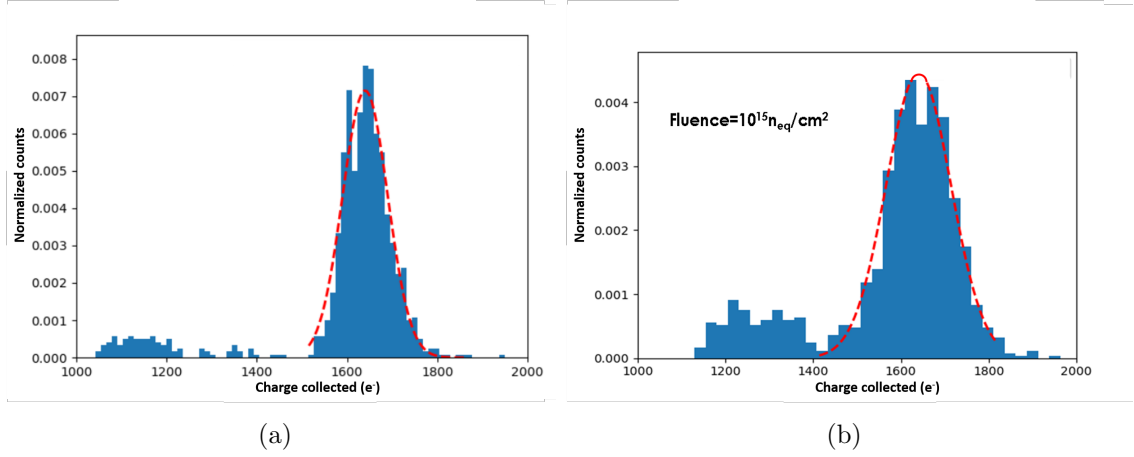


Figure 4.13: ^{55}Fe spectrum obtained with LF-CPIX (a) before and (b) after irradiation.

Edge-TCT

The charge collection properties of the LF-CPIX have been investigated with the edge-TCT technique. Figure 4.14(a) shows the signal as a function of the laser position inside the silicon bulk for different bias voltages. For each bias voltage the depletion depth can be calculated as the FWHM of this distribution, as in Figure 4.14(b). The depletion depth profile as a function of bias voltage has been interpolated with a square root function, and from the extracted parameter the resistivity has been estimated to be $4.2 \pm 0.3 \text{ k}\Omega\cdot\text{cm}$, in agreement with the foundry's specifications. These measurements were taken in a clean room at lab conditions (see Section 3.2).

To check the effect of the irradiation on the charge collection, edge-TCT has been performed on the irradiated devices as well at a temperature of -3°C and 8% humidity (Figures 4.15(a) and 4.15(b)). These results demonstrate that, after being exposed to this fluence, the device can be depleted to a depth of more than $70 \mu\text{m}$ at 140 V bias.

Minimum Ionizing Particle spectrum

The LF-CPIX Version 2 prototype has been exposed to a ^{90}Sr source to obtain the MIP spectrum in lab conditions (see Section 3.2) at 120 V bias (see Figure 4.16(a)). The distribution has then been fitted with a Landau function convoluted with a Gaussian. The MPV extracted from the fit is $\sim 16 \text{ ke}^-$, equivalent to $211 \mu\text{m}$ (see Section 2.2.2.2). This is in good agreement with the value observed with Edge-TCT ($225 \pm 10 \mu\text{m}$). The same procedure has been performed after irradiation at -40°C . In this case, the noise contribution given by low energetic electrons from the source made the peak very hard to recognize. A fit attempt resulted in a MPV of 5244 e^- (see Figure 4.16(b)).

To improve the MIP spectrum of the irradiated LF-CPIX, one of the two irradiated LF-CPIX prototypes has been exposed to a 3 GeV electron beam at the DESY test beam facility at a temperature of -17.5°C . The signal has been collected in coincidence with two scintillators

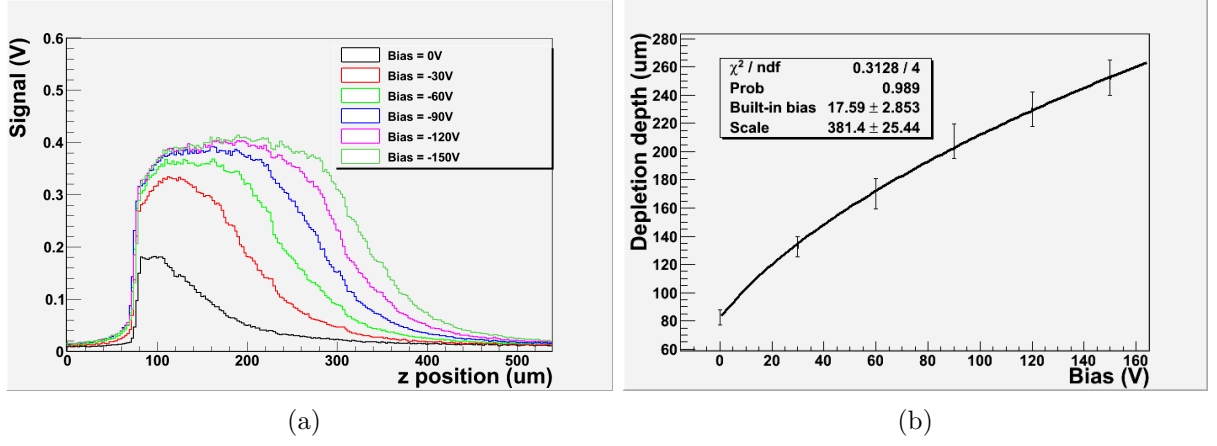


Figure 4.14: (a) Edge-TCT 1D scans of an LF-CPIX active pixel. (b) Depletion depth as a function of bias voltage. The distribution has been fitted with a square root function.

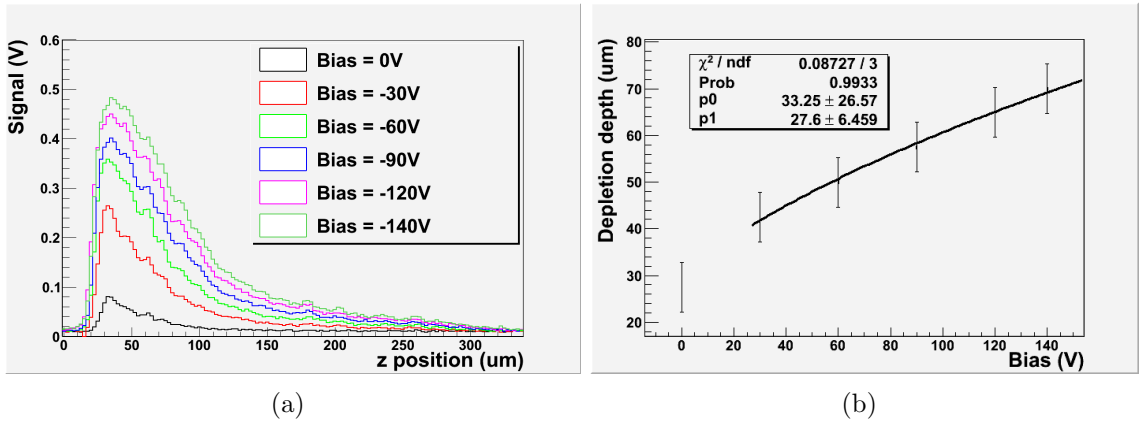


Figure 4.15: (a) Edge-TCT 1D scans of an LF-CPIX active pixel irradiated to $1.0 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$. (b) Depletion depth as a function of bias voltage. The distribution has been fitted with a square root function. The temperature during data taking is -3°C .

at the front and rear edge of the telescope, in order to improve the selection of MIPs. The spectrum of collected charge obtained with this procedure is shown in Figure 4.17. The distribution has then been fitted with a Landau function convoluted with a Gaussian. The result of the fit shows a MPV compatible with 5900 e^- , which corresponds to about $78\text{ }\mu\text{m}$ depletion depth. This value is compatible with the one obtained with the Edge-TCT technique.

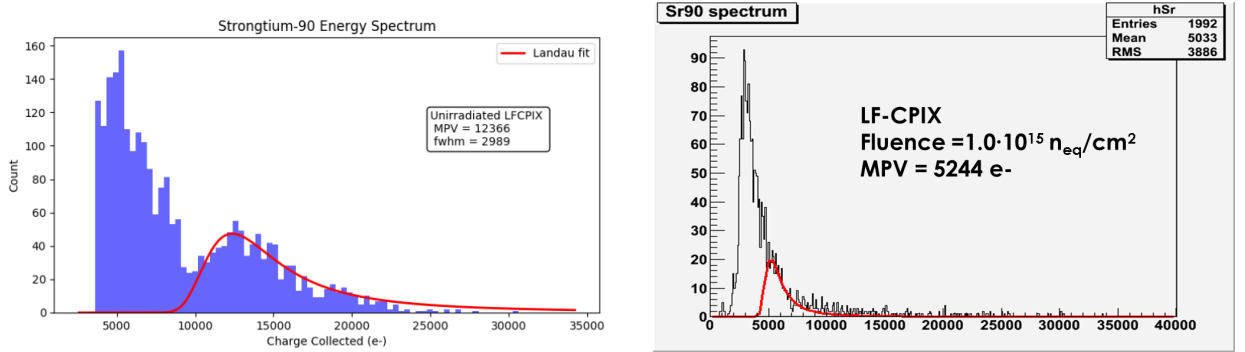


Figure 4.16: Collected charge spectrum obtained with an LF-CPIX prototype exposed to a ^{90}Sr source (a) before and (b) after irradiation to $1.0 \times 10^{15}\text{ n}_{eq}\text{cm}^{-2}$. The distributions have been fitted with a Landau function convoluted with a Gaussian.

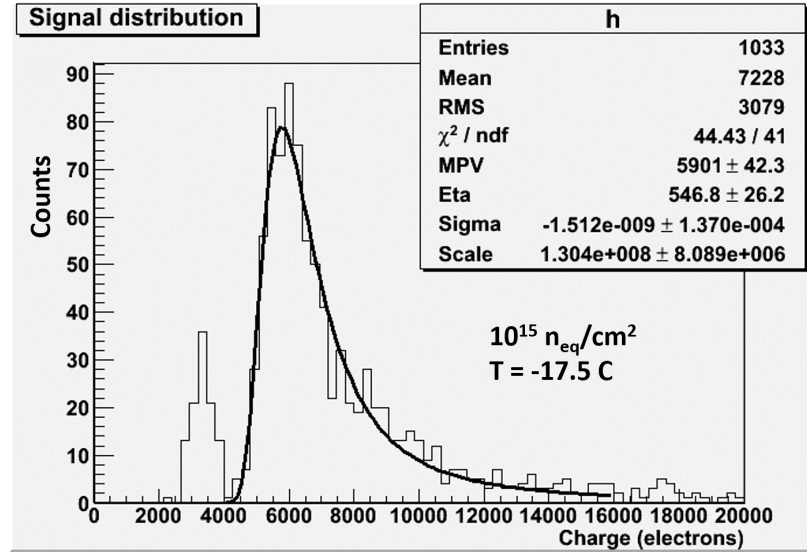


Figure 4.17: Collected charge spectrum obtained with an LF-CPIX prototype irradiated to $1.0 \times 10^{15}\text{ n}_{eq}\text{cm}^{-2}$ and exposed to a 3 GeV electron beam. The distributions have been fitted with a Landau function convoluted with a Gaussian.

Time-walk

Another crucial parameter that has been studied is the time-walk (see Section 2.3.1.2). This is expected to be different for the three preamplifier flavours. To compare the time-walk performance, a LF-CPIX Version 2 has been exposed to Front-TCT and the charge has been

injected uniformly from 4000 to 15000 e^- by varying the laser power (as in Section 3.1.4). Then, the distribution of threshold time against charge collected has been obtained for the three flavours with a threshold of 2000 e^- , a typical value with the ATLAS FE-I4 chips (Figure 4.18). The results show clearly that the PMOS preamplifier has the best performance, with 99% of the signal in the 25 ns range from the hit with the highest pulse height. The other two preamplifiers, instead, show much worse behaviour, with 73% of the hits collected within 25 ns by the CMOS preamplifier and only 31% by the NMOS preamplifier. These measurements were taken in a clean room at lab conditions (see Section 3.2).

The time-walk profile of the irradiated LF-CPIX prototypes has been investigated during the test beam activities at DESY at a temperature of -17.5°C . The resulting 2D distributions of threshold crossing time against collected charge are shown in Figure 4.19. The threshold here was set to 2000 electrons. It can be seen that the performance in this case is significantly deteriorated, as only a small portion of the spectrum lies within 25 ns. If we consider for instance a time-frame of 25 ns from the hit with the highest pulse height, as with the pre-irradiation plots, all three preamplifiers have less than 30 % of the hits within 25 ns. To find the best performance conditions, different portions of the spectrum within a 25 ns band have been considered and for each preamplifier flavour the one with the highest number of hits has been chosen. The resulting “best performance bands” are drawn on the plots of Figure 4.19. Even in these conditions, the portion of hits in the 25 ns band is quite low, reaching only 36% with the NMOS preamplifier, 42% with the PMOS preamplifier and 45% with the CMOS preamplifier.

This poor in-time efficiency is due to the fact that the peaking time of the preamplifiers is rather large (about 200 ns). With a shorter peaking time, the performance can be significantly improved. This is an issue that is currently under investigation by the designers.

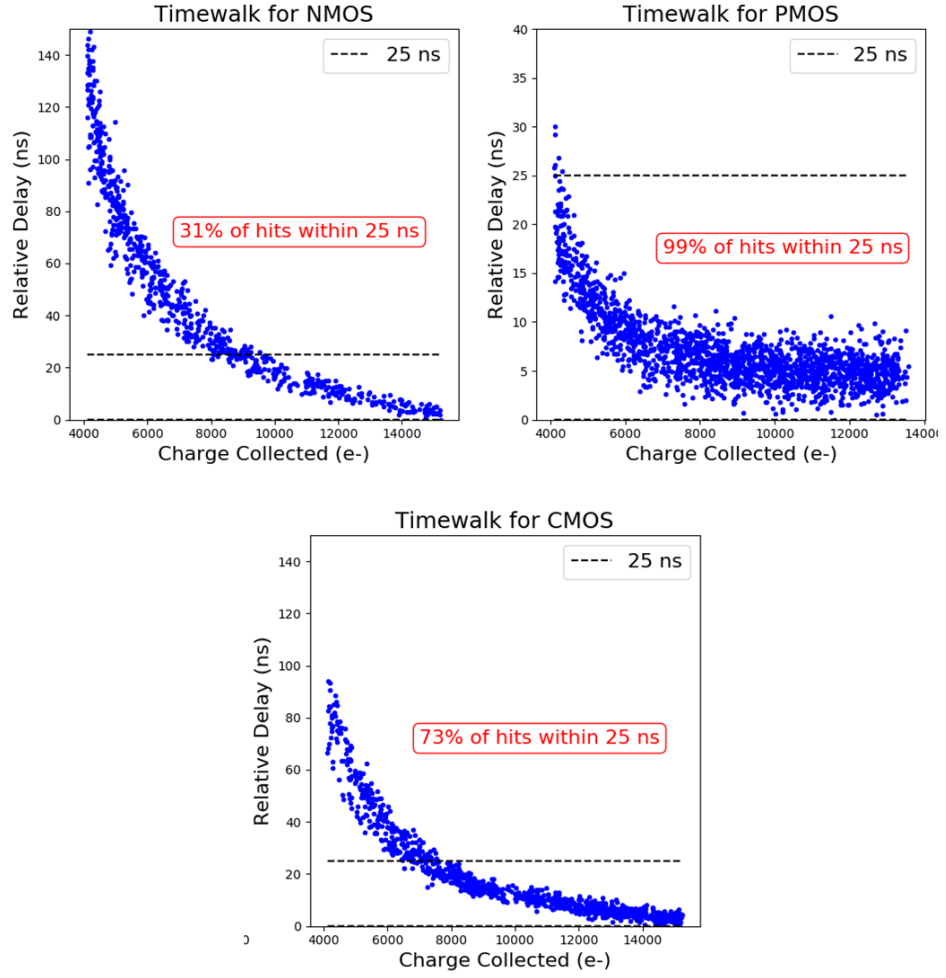


Figure 4.18: Time-walk profile for the three different flavours of LF-CPIX preamplifier: NMOS (upper left), PMOS (upper right), CMOS (lower). On the y axis the time difference between the laser trigger signal and the time-stamp is plotted. The fraction of signal within 25 ns is also reported.

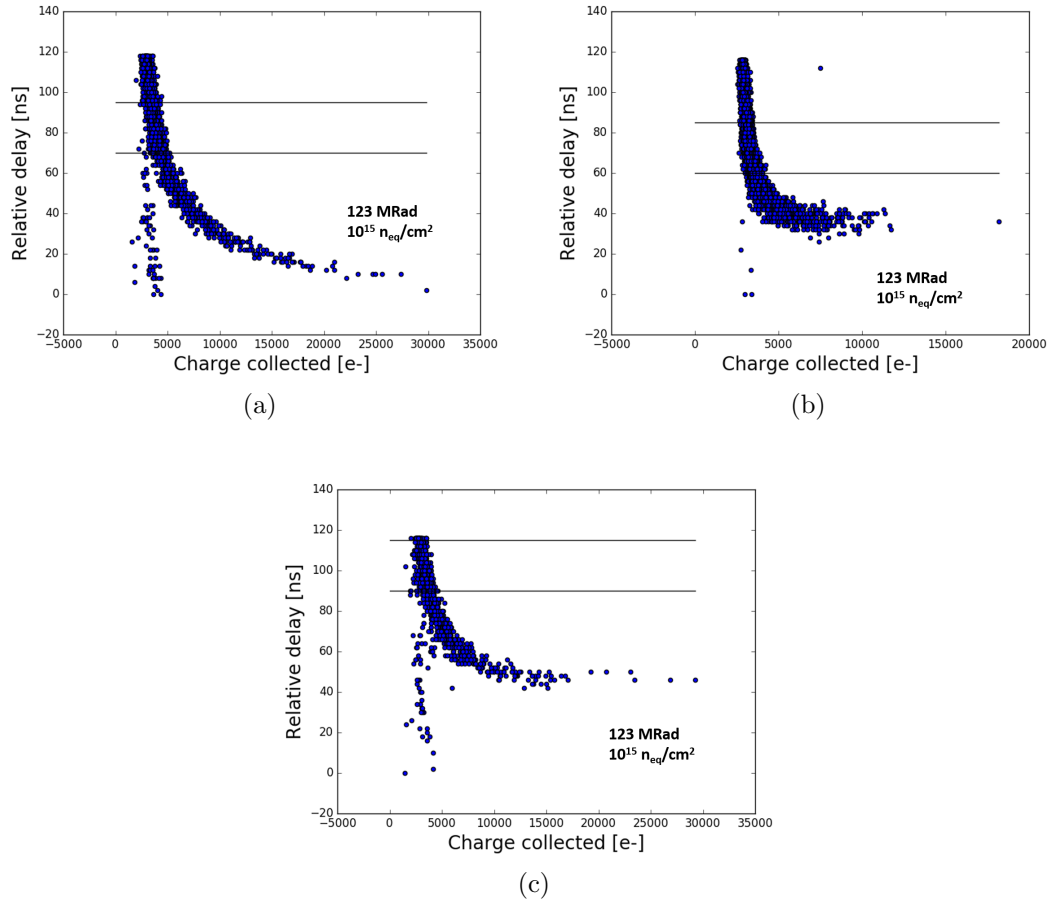


Figure 4.19: Threshold crossing time as a function of charge collected for an LF-CPIX device irradiated to $1.0 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The three preamplifier flavours are reported: NMOS (a), PMOS (b) and CMOS (c). On the y axis the time difference between the scintillator trigger signal and the time-stamp is plotted. The 25 ns “best performance bands” are drawn as horizontal lines.

The results obtained with the LF-CPIX are summarized in Table 4.3.

Test	Before irradiation	After irradiation $1.0 \times 10^{15} \text{ n}_{eq} \text{cm}^{-2}$
IV curve	Version 1: 120 V breakdown Version 2: 210 V breakdown	Version 2: expected increase
Gain	Good	Small reduction (<10%)
Noise	Good	Increase by 34 to 50%
Edge-TCT	4.2 k Ω ·cm resistivity, 250 μm depletion at 150 V	$\sim 70 \mu\text{m}$ depletion at 140 V
^{55}Fe	Good	Good, slight increase in RMS
MIP spectrum	$\sim 211 \mu\text{m}$ depletion depth	$\sim 77 \mu\text{m}$ depletion depth
Time-walk	Good only for PMOS preamplifier	Significantly deteriorated

Table 4.3: Summary table of the tests performed on the LF-CPIX.

4.1.3 LF-MONOPPIX

4.1.3.1 Description

The next device produced with the LFoundry 150 nm technology is the LF-MONOPPIX, a fully monolithic device [84]. Digitization of the signal was added to the in-pixel read-out design of the LF-CPIX. In particular, a column drain read-out architecture very similar to the FE-I3 chip, with an internal clock of 40 MHz was implemented. The pixel matrix consists of 36×129 pixels, each $250 \times 50 \mu\text{m}^2$, for a total size of $1 \times 1 \text{ cm}^2$.

While taking data, if a pixel's signal is higher than the threshold, the comparator enables a HIT flag. The time at which the comparator output rises (leading edge) and falls (trailing edge) is recorded in an internal clock unit (25 ns sampling time). The Time over Threshold (ToT) can be computed as the difference between the two time stamps. The data are serialized and sent off-chip at a rate of 160 Mbps by an LVDS driver.

4.1.3.2 Pre-irradiation results

At the time of writing this thesis, only pre-irradiation results are available for LF-MONOPPIX devices, as the irradiation campaign took place at a later stage.

IV curves

The IV curve obtained with the LF-MONOPIX at lab conditions (see Section 3.2) in Figure 4.20 shows a breakdown voltage of about 250 V, even higher than the previous prototypes.

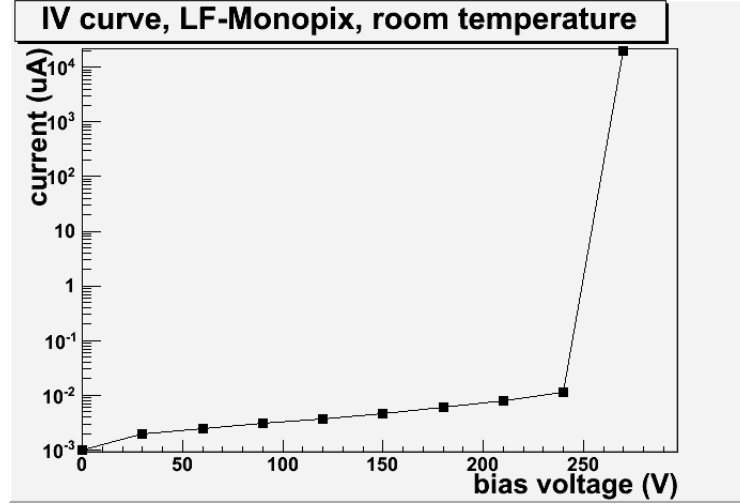


Figure 4.20: IV curve for the LF-MONOPIX.

Time-walk

The time-walk profile of the LF-MONOPIX has been studied at lab conditions (see Section 3.2). Charge injection has been performed at steps of 100 mV in order to obtain a uniform distribution of charge collected, then the mean leading edge time (i.e. the time of threshold crossing) has been recorded as a function of the ToT (see Figure 4.21). The plot shows a maximum time-walk of 50 ns, which does not meet the LHC requirements.

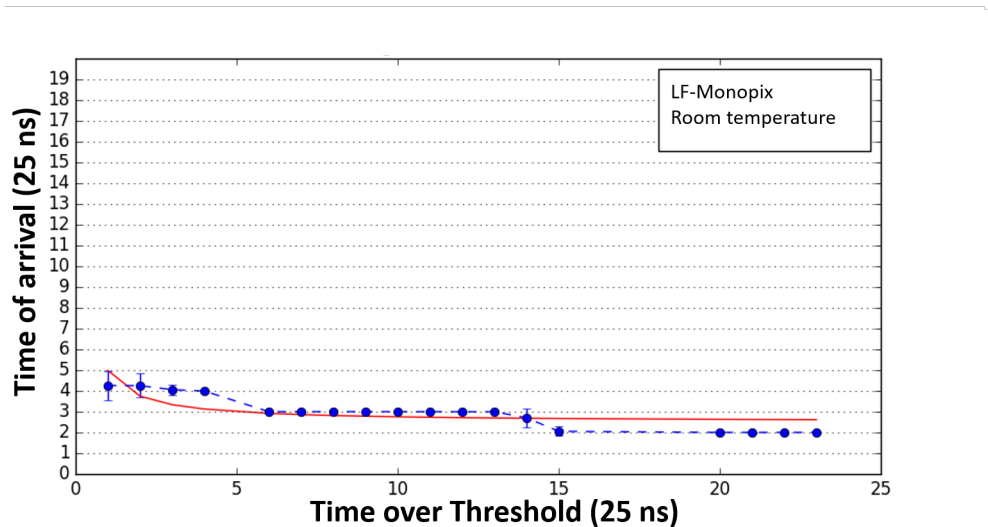


Figure 4.21: Leading edge position as a function of ToT for the LF-MONOPIX.

Edge-TCT

The LF-MONOPIX prototype has then been tested with the Edge-TCT technique at lab conditions (see Section 3.2). The profile of signal as a function of depth is shown in Figure 4.22(a). The distributions show a dip at about $150\text{ }\mu\text{m}$, but that is likely due to the fact that the board was not designed for Edge-TCT, and the laser path may be obstructed. This dip appears in other pixels at different z positions.

Figure 4.22(b) shows the depletion depth as a function of bias. This plot has been fitted with a square root function and the extrapolated resistivity is compatible with $3.9 \pm 0.2\text{ k}\Omega\cdot\text{cm}$, a value in agreement with the foundry specifications.

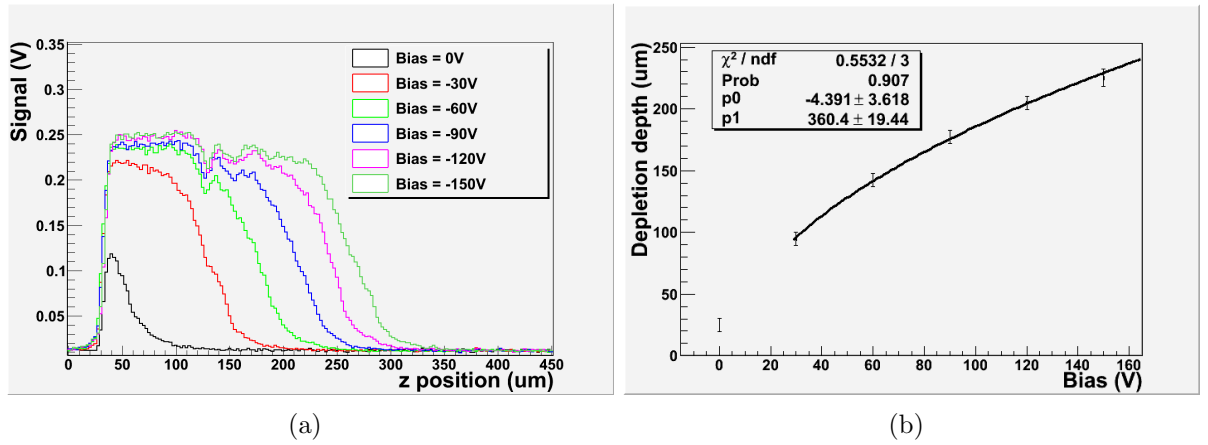


Figure 4.22: (a) Edge-TCT 1D scans of an LF-MONOPIX active pixel after proton irradiation. (b) Depletion depth as a function of bias voltage. The distribution has been fitted with a square root function.

The results obtained with the LF-MONOPIX are summarized in Table 4.4.

Test	Before irradiation
IV curve	250 V breakdown
Time-walk	Larger than required (50 ns)
Edge-TCT	$3.9\text{ k}\Omega\cdot\text{cm}$, $230\text{ }\mu\text{m}$ depletion at 150 V

Table 4.4: Summary table of the tests performed on the LF-MONOPIX.

4.2 CMOS passive pixel sensors

4.2.0.3 Description

Passive CMOS sensors from LFoundry were also investigated and those studies are reported here. They are simpler than active CMOS devices since the read-out of the silicon will be done by an external chip. The advantage of devices with respect to hybrid pixels, then, is that they can be manufactured by the foundry with bump bonds already deposited on the sensor surface. The bump bonding process is therefore cheaper.

Prototype n-in-p pixel sensors of this technology have been produced on p-type wafers of 3-5 k Ω ·cm resistivity [90]. The pixel matrix consists of 16×36 pixels, each $50 \times 250 \mu\text{m}^2$. The electrodes in the matrix are isolated from the high voltage at the sensor edge by a guard ring structure that includes an n-implant and seven p-implants (see Figure 4.23). Half of the pixels are DC coupled with punch-through biasing and the other half are AC coupled by a Metal-Insulator-Metal (MIM) capacitor. In the two outermost columns of the DC half, the n-implant width varies in the range between $15 \mu\text{m}$ and $30 \mu\text{m}$. This feature is used for optimization studies of the fill factor.

The sensors have been thinned to $100 \mu\text{m}$ and $300 \mu\text{m}$ and then backside-processed providing a p-implant and a metalization layer to allow bias voltage application from the backside.

Since this prototype does not have the read-out electronics implemented inside the silicon bulk, a front end read-out chip is needed. Given the pixel size of these sensors, FE-I4 chips were chosen for their read-out.

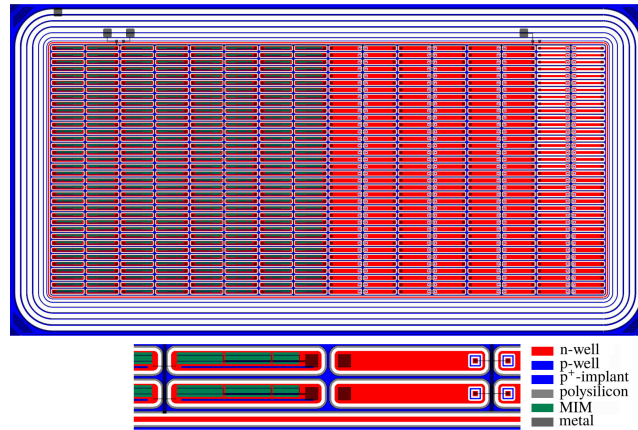


Figure 4.23: Passive CMOS sensor layout [90].

4.2.0.4 Results

Irradiation

One prototype has been irradiated at Birmingham MC40 facility in two steps, up to 0.18×10^{15}

$n_{eq}\text{cm}^{-2}$ and then $1.14 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$.

IV curves

After assembly, the IV curves were obtained for prototypes with different thicknesses (see Figure 4.24). The 300 μm thick prototypes show a breakdown voltage of about 170 V. The 100 μm prototype did not undergo plasma etching after thinning, and that may be the reason why the sensor shows a lower breakdown voltage after full depletion, as already observed before [91].

After irradiation, the leakage current increases as expected. Furthermore, the breakdown voltage increases, as the devices could be biased up to 700 V without observing any breakdown.

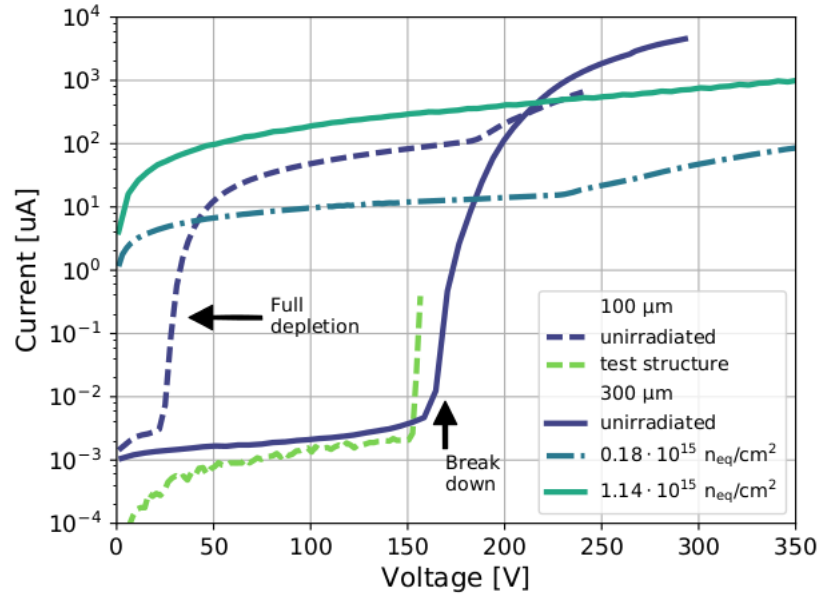


Figure 4.24: IV curves for the passive CMOS sensor [90].

Minimum Ionizing Particles spectrum

The prototypes were then investigated in a test beam with a 3.2 GeV electron beam at the ELSA facility in Bonn. The profile of charge collected at 160 V bias follows a Landau distribution with an MPV of about 19 ke^- before irradiation and 14 ke^- after a dose of $0.18 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$ (see Figure 4.25(a)).

Since the MPV is directly proportional to the depletion depth (see Section 2.2.2.2), the profile of the depletion depth as a function of the bias voltage can be obtained by computing the MPV values at different bias voltage steps, as shown in Figure 4.25(b). The results are compatible with a resistivity of 4 to 5 $\text{k}\Omega\cdot\text{cm}^2$.

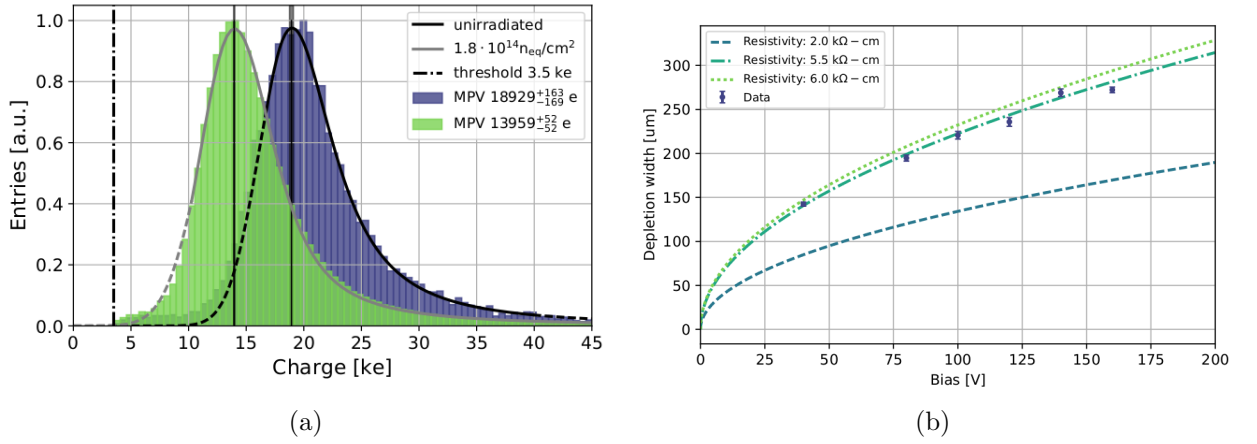


Figure 4.25: (a) Charge distribution for passive CMOS detector prototypes before irradiation (blue) and after a fluence of $0.18 \times 10^{15} n_{eq} cm^{-2}$ (green). The MPV values are reported in the legend. (b) Depletion depth as a function of bias voltage obtained from the charge distribution fits [90].

Efficiency

The test beam at the ELSA facility employs a telescope consisting of two FE-I4 planes. Given the small amount of planes, the resolution is not sufficient to perform in-pixel efficiency scans. Nevertheless, the total efficiency could be computed for different devices and voltages by predicting the hit position with the telescope and checking the presence of hits in the predicted pixel and the surrounding ones. The results are shown in Figure 4.26.

Generally, the DC-coupled pixels show a lower efficiency than the AC-coupled ones. This can be due to the non-sensitive area taken by the structures used for the punch-through biasing. Before irradiation, at a threshold of $3000 e^-$, the $100 \mu m$ thick device has an efficiency of 98.7% for the DC-coupled pixels and 99.8% for the AC-coupled pixels. If the threshold is reduced to $1500 e^-$, the efficiency improves to 99.8 % and 99.9% respectively. The results for the $300 \mu m$ thick device are compatible with the $100 \mu m$ thick one. After irradiation, the $300 \mu m$ thick device show an efficiency of 99.9% with AC coupled pixels at 350 V even after a fluence of $1.14 \times 10^{15} n_{eq} cm^{-2}$.

These results are very promising, as they prove the device is highly radiation-hard.

Pixel efficiency

As mentioned before, the telescope at the ELSA test beam did not have a sufficient resolution to compute in-pixel efficiency. Nevertheless, the telescope has been exploited to compute single pixel efficiency. The result is shown in Figure 4.27(a). This distribution shows a uniform efficiency in the inner part of the sensor, while the outer columns and rows have a lower efficiency. In particular, when focusing on the right-most column, one can notice a variation of efficiency as a function of the n-implant width (see Figure 4.27(b)). More specifically, the efficiency is higher for a larger n-implant width (i.e. fill factor).

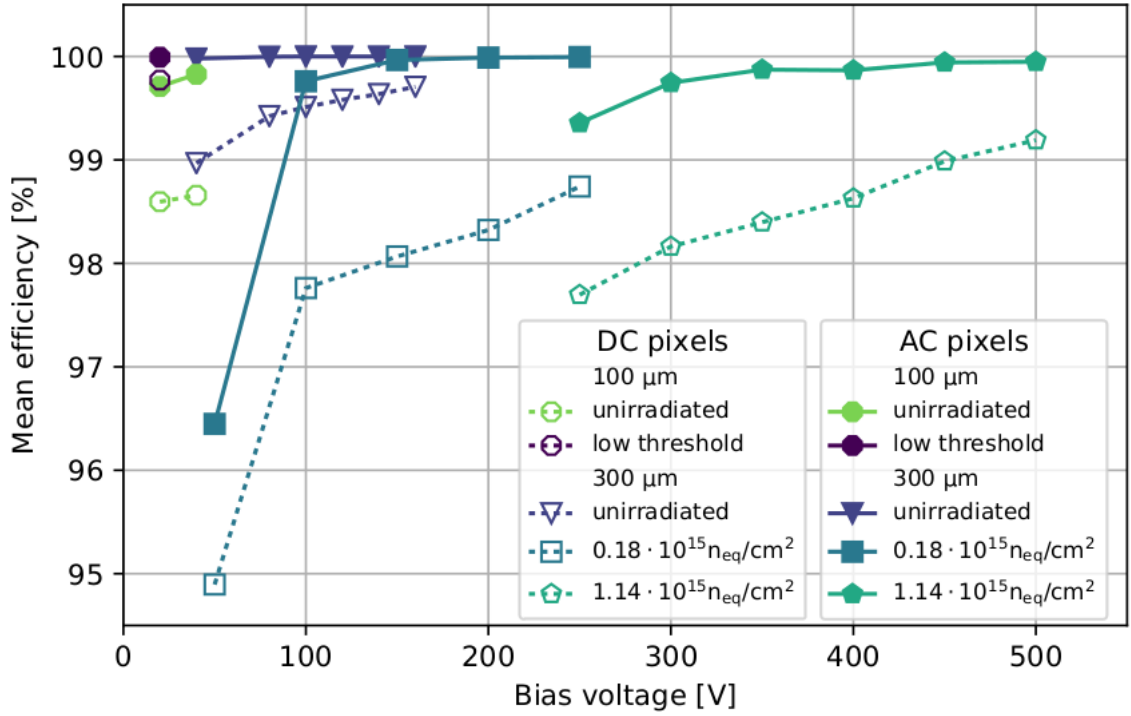


Figure 4.26: Efficiency as a function of bias voltage for different structures, thicknesses, threshold and radiation doses [90].

This behaviour is confirmed by the relative efficiency computed for an unirradiated device with an X -ray source (see Section 3.6). The relative efficiency map is shown in Figure 4.28. From this map, one can notice that the efficiency is slightly lower for the DC-coupled pixels than for the AC-coupled pixels. A difference in efficiency for the pixels in the right-most column is observed as well. In this case, though, this difference is more pronounced than in the efficiency map computed in the test beam. This can be due to the poor resolution of the telescope, which smears the efficiency distribution.

Front-TCT

Since the passive CMOS prototype does not have any metalization on the surface, the signal uniformity could be inspected with the Front-TCT technique on an unirradiated device with an infrared laser under lab conditions (see Section 3.2). The average ToT and cluster size are shown in Figure 4.29(a) and 4.29(b) respectively. Although the plot shows some tilting around the laser beam axis, it is clear that the distributions follow the expected patterns. The average ToT, indeed, is higher in the centre of the pixel, and decreases slightly at the borders due to charge sharing. For the same reason, the average cluster size is instead lower in the centre and can be as high as 4 on the borders.

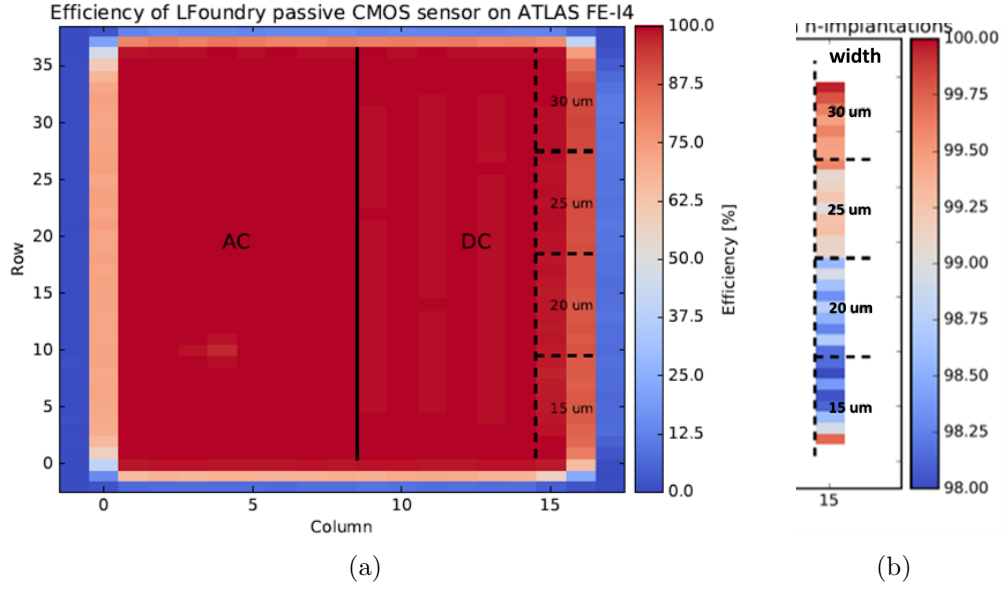


Figure 4.27: (a) Efficiency map of a passive CMOS sensor obtained with 3.2 GeV electrons at ELSA (Bonn). (b) Efficiency map of the right-most column of pixels, which consists of pixels with different n-implant widths.

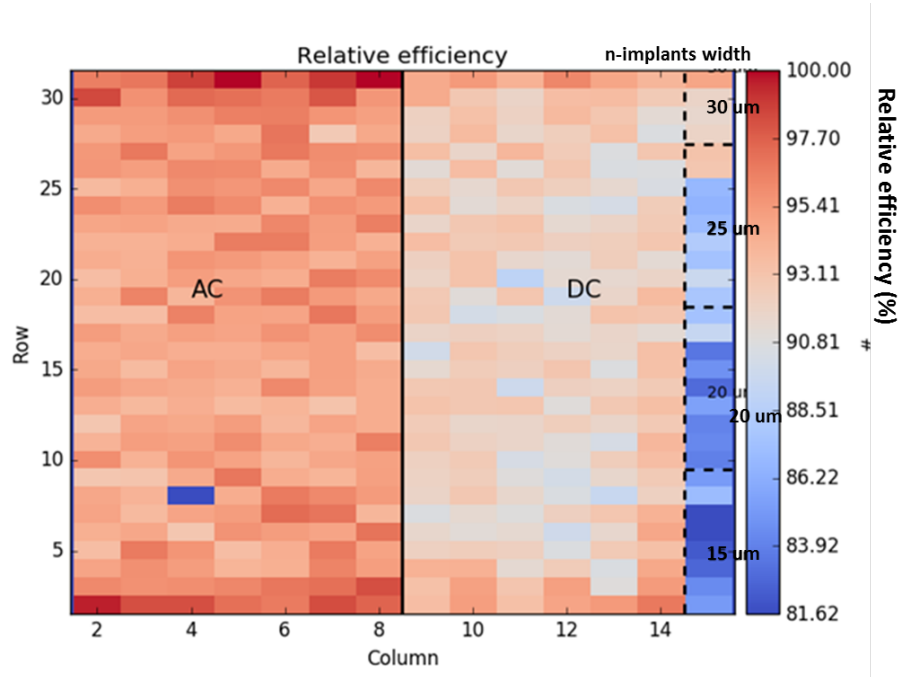


Figure 4.28: Relative efficiency map for a CMOS passive prototype.

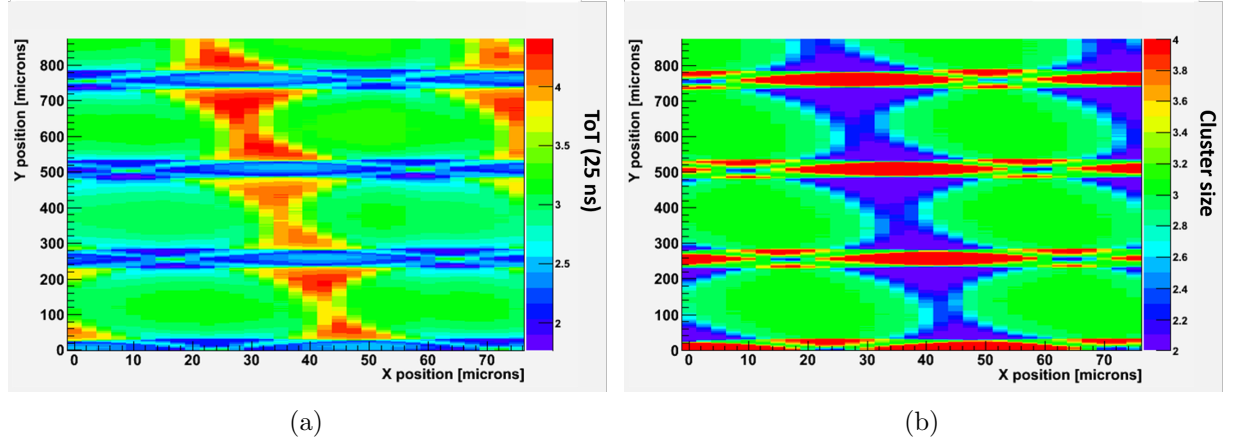


Figure 4.29: (a) Mean ToT as a function of laser position on the surface of the passive CMOS prototype obtained with the Front-TCT technique. (b) Mean cluster size as a function of laser position on the surface of the passive CMOS prototype obtained with the Front-TCT technique.

The results obtained with the LFoundry passive CMOS prototype are summarized in Table 4.5.

Test	Before irradiation	After irradiation $0.18\text{-}1.14 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$
IV curve	170 V breakdown after plasma etching	Good
MIP spectrum	19 ke ⁻ MPV	14 ke ⁻ MPV ($0.18 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$)
Efficiency	Up to 99.9% at 150 V bias	Up to 99.9%, 350 V bias, ($1.14 \times 10^{15} \text{ n}_{eq}\text{cm}^{-2}$)
Pixel efficiency	DC- less efficient than AC-coupled Larger the collection diode → larger efficiency	Confirmed
Front-TCT	Expected behaviour	Not Available

Table 4.5: Summary table of the tests performed on LF passive CMOS prototype.

4.3 CMOS strip detectors

In the framework of the ATLAS ITk, the CMOS technology has been considered also for a novel silicon strip detector. In this case, the flexibility of the CMOS technology is exploited to produce a sensor with the precision of a pixel detector and the read-out simplicity of a strip detector. In this design the information about the column is encoded in the pixel circuitry, while the information about the row is given by an external chip which acts like a strip read-out chip. This way, these devices don't need bump bonding to be connected to the chip, but just wire bonded. As they need an external chip, these detectors are considered active CMOS sensors, but the advantages can be comparable to the monolithic ones [92]. Given their special read-out strategy, these devices are familiarly referred to as “strixels”. The design implemented for these prototypes is based on the AMS H35 350 nm technology. The AMS foundry provides p-type substrates of $20 \Omega\cdot\text{cm}$ resistivity.

As far as this thesis is concerned, two prototypes based on this technology have been investigated: HVStrip1 and Chess1. These are the first two iterations of an R&D project towards a final demonstrator.

4.3.1 HVStrip1

4.3.1.1 Description

The HVStrip1 prototype has several different test structures, such as NMOS and PMOS transistors, a passive diode, and a 22×2 array of active pixels. Each of these pixels has a size of $40 \times 400 \mu\text{m}^2$. The active pixels implement a preamplifier and a comparator that can be configured to adjust for time-walk effects. The analogue output of one of the pixels can be chosen to be sent through a dedicated board to an oscilloscope. The layout of a single pixel can be seen in Figure 4.30.

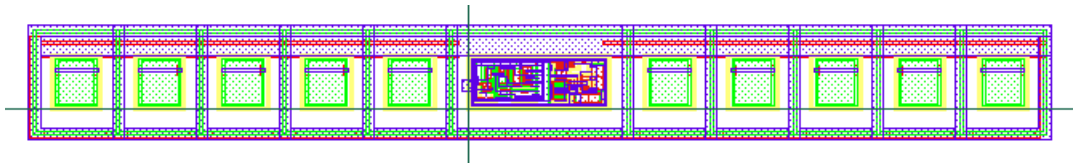


Figure 4.30: Layout of a HVStrip1 single pixel.

In addition, HVStrip1 has been designed with two different kinds of front-end amplifiers. More specifically, the pixels in the array from columns 0 through 7 have a standard linear transistor in the feedback loop of the circuit, whilst those from columns 8 through 21 contain another kind of transistor, named circular transistor. In this configuration, the linear

transistor is expected to have a higher gain than the circular transistor before irradiation [92].

4.3.1.2 Results

IV curve

The IV curve taken under lab conditions (see Section 3.2) of the HVStrip1 show a good behaviour, with a leakage current of about 30 nA at 60 V bias.

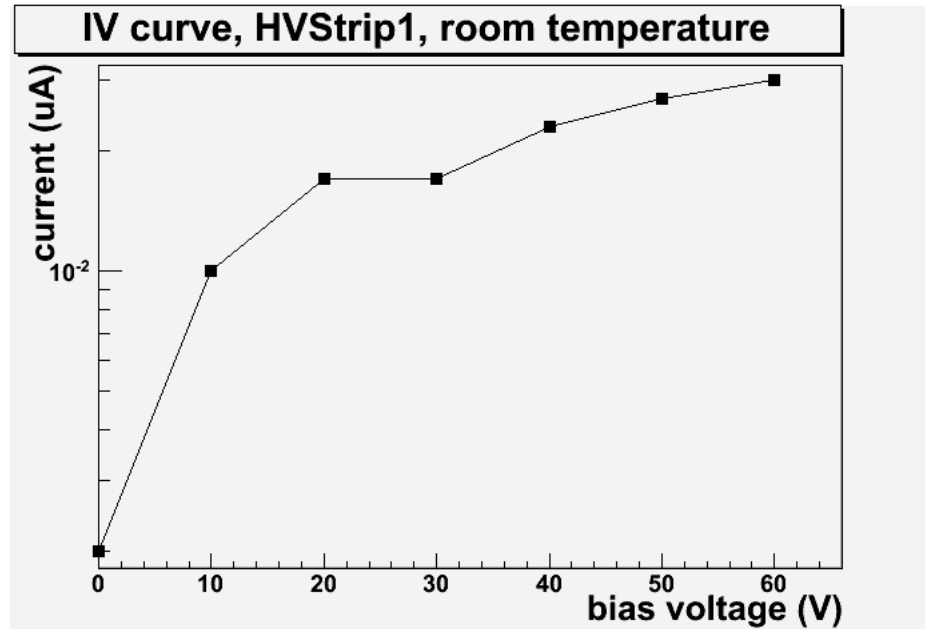


Figure 4.31: IV curves for the HVStrip1.

^{55}Fe spectrum

The HVStrip1 prototype has been exposed to an ^{55}Fe source under lab conditions (see Section 3.2) and the spectra for all the pixels collected. One of the spectra is shown in Figure 4.32(a), where the full-absorption peak is clearly visible. The position of the full absorption peak has then been used to compute the gain of the preamplifier for every pixel (see Figure 4.32(b)). To obtain this, the peak is fitted with a Gaussian and the mean value is converted from millivolts, the output units, into the expected charge released, which is 1640 e^- , equivalent to 0.26 fC. The gain map obtained with this method clearly shows the difference between pixels with a linear transistor (columns 0-8) and pixels with a circular transistor (columns 9-21), as the former has a higher gain than the latter.

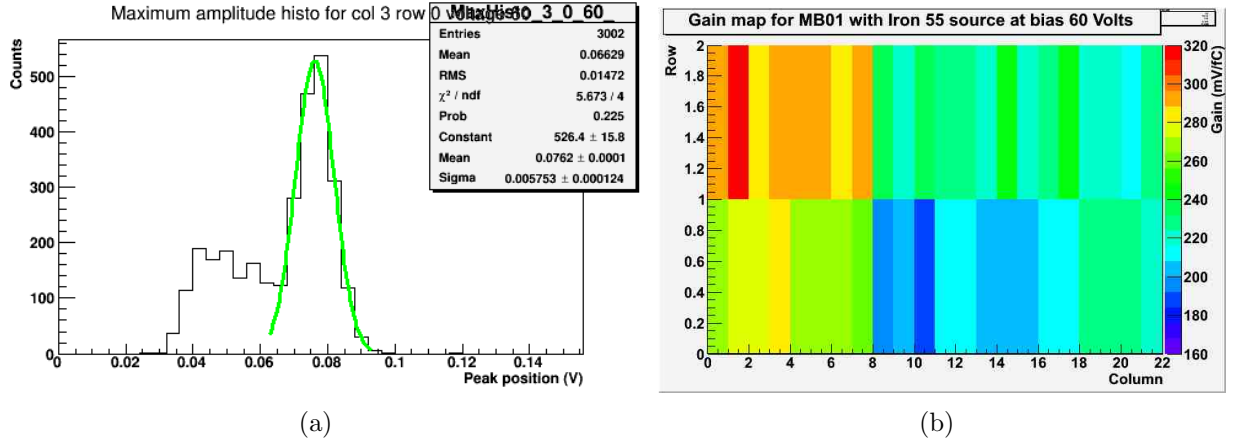


Figure 4.32: (a) ^{55}Fe spectrum obtained with the HVStrip1. (b) Gain map of the HVStrip1 obtained by fitting the full-absorption peaks of the ^{55}Fe spectra.

Test beam

HVStrip1 prototypes have been placed in a beam line at DESY and tested with 3 GeV electrons. A distribution of collected charge has been obtained for all the pixels to check the uniformity of response. An example of a MIP spectrum obtained with a HVStrip1 biased to 60 V is shown in Figure 4.33(a). The distributions are then fitted with a Landau function convoluted with a Gaussian, and the MPV value is extracted from the fit. The complete map of the MPV values can be found in Figure 4.33(b). The distribution across the pixel matrix is quite uniform, with an average MPV value of about 1700 e^- , which corresponds to a depletion region of 22 μm .

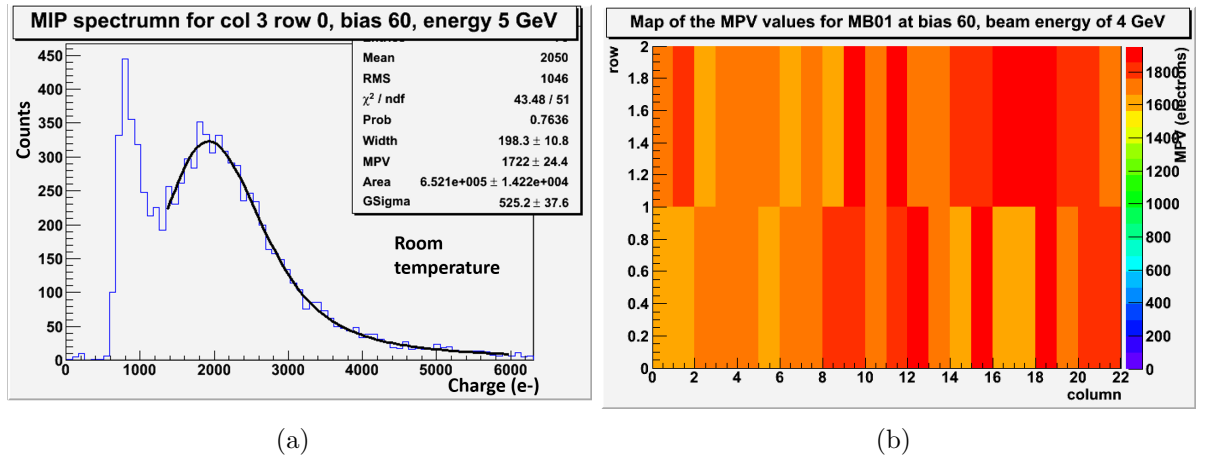


Figure 4.33: (a) Electron beam spectrum obtained with an HVStrip1 pixel. The device was biased to 60 V. (b) Complete MPV map obtained by fitting the charge distributions of 3 GeV electrons.

Irradiation

Two HVStrip1 prototypes were irradiated at the Birmingham MC40 facility to a fluence of

$0.8 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$. They were successively tested with a ^{90}Sr source at -20°C . The obtained spectrum is shown in Figure 4.34. The signal is significantly degraded, and it could be extracted only from the pixels with a circular transistor. The distribution then has been fitted with a Landau function convoluted with a Gaussian and summed to an exponential function, which takes into account the background contribution. The MPV then has been estimated to be 1053 electrons, which corresponds to a depletion region of about $14 \mu\text{m}$.

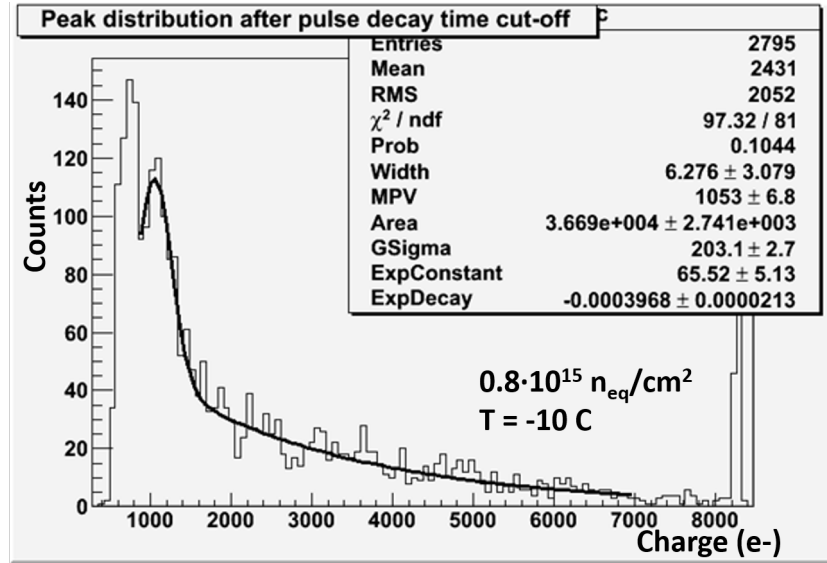


Figure 4.34: ^{90}Sr spectrum obtained with a HVStrip1 device irradiated to $0.8 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$.

The results obtained for the HVStrip1 are summarized in Table 4.6.

Test	Before irradiation	After irradiation $0.8 \times 10^{15} \text{ n}_{eq} \text{ cm}^{-2}$
IV curve	Good	Not Available
^{55}Fe	Good, gain as expected	Not Available
MIP spectrum	1700 e^- MPV	$\sim 1050 \text{ e}^-$ MPV, large noise

Table 4.6: Summary table of the tests performed on the HVStrip1.

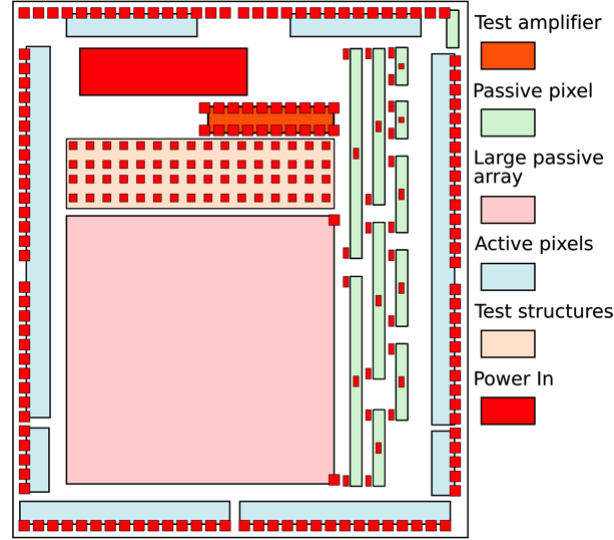


Figure 4.35: Layout of the Chess1 prototype with its components.

4.3.2 Chess1

4.3.2.1 Description

The Chess1 test detector is the second prototype implemented in the AMS H35 process. This device contains several different test structures, including passive and active CMOS (see Figure 4.35). This thesis shows results only on the active structures. These structures come in blocks of 9 pixels, named Active Pixel Arrays (APA). The pixel blocks have four different sized pixels, ranging from $45 \times 100 \mu\text{m}^2$ to $45 \times 800 \mu\text{m}^2$, and two different fill factors, 33% and 50%, for a total of 8 combinations. All active pixels have the same type of amplifier attached to the sensing diode.

4.3.2.2 Results

Front-TCT

The Chess1 prototype has been tested with the Front-TCT technique at lab conditions (see Section 3.2) to verify the layout of the APAs. Examples of APA signal distributions obtained with this technique are shown in Figure 4.36. Given that there is some metalization between collection wells, it is visible in the plots that APA2 has two collection wells, APA5 and APA6 has four and APA8 has 8. Also, one can notice the different fill factor for APA5 with respect to APA6. These results are all in agreement with the design.

Edge-TCT

In addition, the Edge-TCT technique has been performed on a Chess1 prototype under lab conditions (see Section 3.2) to verify the extension of the depletion region. The plots of

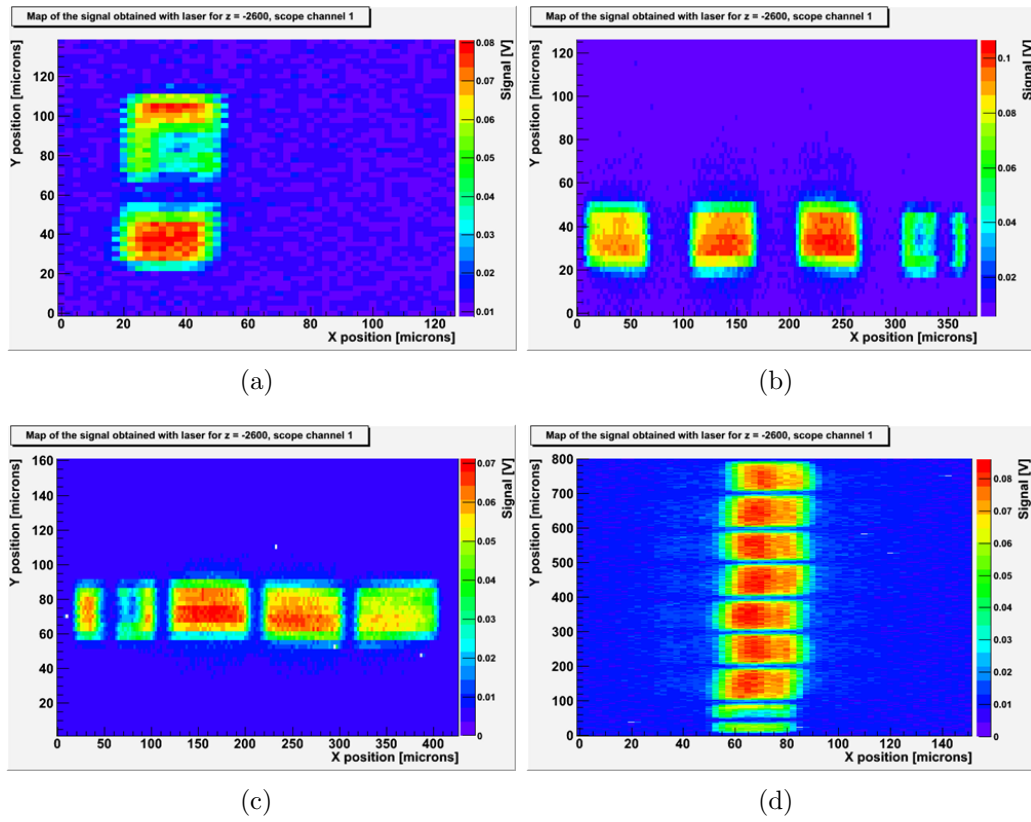


Figure 4.36: Front-TCT signal distribution for a Chess1 prototype. The investigated structures are (a) APA2, (b) APA5, (c) APA6 and (d) APA8.

signal distribution at different bias voltages can be found in Figure 4.37. In this case, the profile of the distributions does not show a plateau typical of a depletion region, and the depletion depth could not be estimated.

These results are confirmed by the fact that the spectra with ^{55}Fe and ^{90}Sr could not be obtained, as the devices do not respond properly to small charge injections. Furthermore, the leakage current is quite high with these devices, as it reaches few mA at 80 V bias. This might be due to some faults in the layout of the wells, which leads to an improper biasing of the sensor.

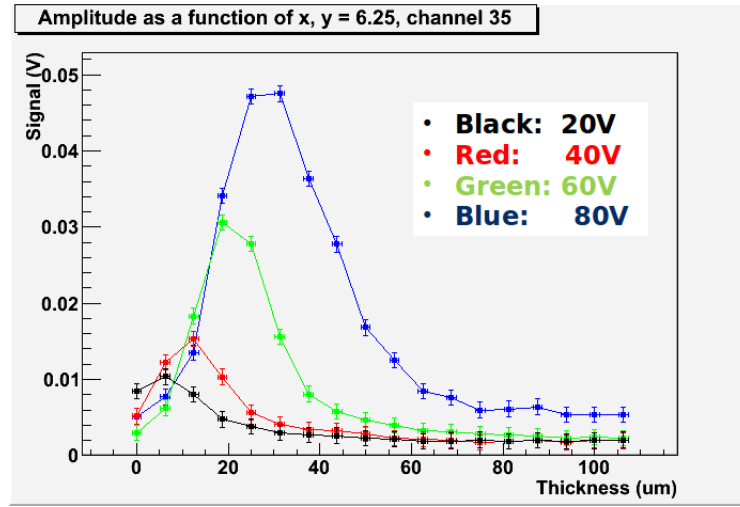


Figure 4.37: Signal as a function of depth obtained with Edge-TCT technique on a Chess1 prototype at different biases.

The results obtained with the Chess1 are summarized in Table 4.7.

Test	Before irradiation
Front-TCT	As expected
Edge-TCT	No depletion region observed

Table 4.7: Summary table of the tests performed on Chess1.

4.4 Summary

The results shown in this chapter about the CMOS sensors for high energy physics are promising. Two LFoundry prototype devices, the CCPD_LF and the LF-CPIX, show a good signal-to-noise ratio both before and after irradiation. In particular, the CCPD_LF prototype shows a large depletion region with the Edge-TCT technique before (Section 4.1.1.2)

and after (Section 4.1.1.3) irradiation to doses which exceed the ITk expected dose. Also the behaviour with MIPs and X -rays before irradiation (Section 4.1.1.2) is compatible with the expectations.

The LF-CPIX prototype has been extensively studied and its performance has been analyzed before and after irradiation to two thirds of the expected dose at the ITk (Section 4.1.2.2). The signal-to-noise ratio is shown to be large enough with Edge-TCT, ^{55}Fe and MIPs both before and after irradiation. The electronics show a good resistance to the irradiation damage in terms of gain and noise. Nevertheless, the in-time efficiency measured with the time-walk is significantly degraded after irradiation, since the preamplifier output is considerably slower than the requirements of ATLAS. This issue must be addressed in the next step of the LFoundry project.

The results collected with the LF-MONOPIX before irradiation (Section 4.1.3.2) show an improvement in the breakdown voltage from LF-CPIX, and the resistivity estimated with the edge-TCT technique is in agreement with the foundry specifications. The in-time efficiency, like LF-CPIX, is not satisfactory for the HL-LHC requirements. The results after irradiation are not available thus far, but given the results before irradiation the outlook is promising.

Thanks to these results, the LFoundry technology has been considered for the ITk pixel system. The LFoundry CMOS sensor project is still under development, and the next step is to build a fully monolithic module compatible with the ITk read-out system.

The other kind of CMOS sensor technology studied for the ITk is the LFoundry passive CMOS sensor technology. The results collected with the prototypes of this technology (Section 4.2.0.4) are very interesting. The efficiency has been measured with a test beam and it is shown to be almost 100% even after irradiation to a dose close to the expected ITk dose. The MIP spectra and the investigation with Front-TCT show a good agreement with the expectations. Moreover, the IV curves show quite a high breakdown voltage before and after irradiation. Furthermore, the investigation of the relative pixel efficiency shows that the efficiency is higher with larger fill factor, which is a very interesting feature and must be considered when designing these devices.

Even though the passive CMOS technology looks quite promising, the monolithic sensors are still the only option considered for the ITk pixels [47].

Along with the CMOS pixel sensors, also the CMOS strip sensors have been considered for the ITk. In this case, the prototypes have been produced with the AMS technology. Unfortunately, the results collected are not satisfactory. Given the relatively low resistivity and breakdown voltage, the HVStrip1 prototype (Section 4.3.1.2) shows a small signal-to-noise ratio with MIPs before irradiation. The signal-to-noise ratio is degraded after irradiation, since the noise is significantly larger.

The Chess1 prototype (Section 4.3.2.2) does not show a good performance, since no de-

pletion region has been observed with the Edge-TCT before irradiation and no results have been collected after irradiation.

The failure of the CMOS strip project shows that the implementation of the depleted CMOS technology is not simple and requires a substantial effort to become mature enough for high energy particle physics experiments.

Chapter 5

The $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis

The discovery of the Higgs boson was a milestone in the history of Particle Physics, as it confirms the Electroweak Symmetry Breaking mechanism proposed by the Standard Model (SM). Nevertheless, many of its features must still be investigated.

This chapter starts with an introduction to the physics of the Higgs boson and its production and decay mechanism at the LHC. Later, we will introduce the specific decay mode this thesis focuses on, i.e. the Higgs boson decaying to two Z bosons which subsequently decay to a lepton $\ell(= e, \mu)$ and a neutrino pair (for this reason the analysis is referred to as the $\ell\ell\nu\nu$ analysis). Afterwards, the details of this analysis will be outlined, starting from the motivation, moving then to the description of analysis objects, to the search strategy and finally to the description of the various backgrounds.

5.1 Higgs boson physics

5.1.1 Symmetry Breaking

This section will provide a brief description of the Higgs mechanism. A detailed discussion can be found in many text books and articles, including [\[93\]](#).

In the Standard Model, particle interactions are based on gauge-invariant symmetries. According to this model, every theory introduces an algebraic group under which the Lagrangian must be invariant (for instance, $U(1)$ for Quantum Electrodynamics). To preserve this invariance, an additional gauge field must be added to the Lagrangian. This field introduces one or more bosons, which act as mediators for the interactions.

In the case of the weak interaction, the invariance group is $SU(2)^W$, the group of weak isospin. The fact that these interactions are limited in range suggests that the mediator bosons are massive. The introduction of the gauge boson mass term in the Lagrangian, however, breaks the gauge invariance and makes the theory non-renormalisable. To overcome

this problem, the Spontaneous Electroweak Symmetry Breaking mechanism was proposed. In this mechanism, a complex scalar field with a non-zero vacuum expectation is added to the Lagrangian. The Lagrangian is required to be invariant under a $U(1)$ transformation of this field. The function describing this field, however, has a local maximum at zero, while the local minima form a circle in the complex plane with radius equivalent to the vacuum expectation. This shape is familiarly known as the Mexican Hat (see Figure 5.1). Therefore, by re-writing the Lagrangian in terms of the lowest energy state, the global invariance is violated and the symmetry is broken. This gives rise to two particles: a massive scalar particle and a massless “Goldstone” boson. By requiring the Lagrangian to be locally invariant, the extra massless boson is “eaten” by the massive boson. The symmetry breaking mechanism was first proposed by Peter Higgs for a generic Lagrangian [94], thus the particle is named the Higgs boson.

The symmetry breaking mechanism was then introduced in the Standard Model by Glashow, Weinberg and Salam. According to this model, the invariance group of electroweak interactions is the combined $SU(2)_L \times U(1)_Y$ (see Section 1.1) [95, 96]. When the symmetry breakdown mechanism is applied to it, the $U(1)$ QED gauge invariance remains unaltered, leaving the photon massless. On the other hand, the $SU(2)_L$ symmetry is broken and its bosons (the $W^\pm$ and the Z) acquire mass by absorbing the Goldstone boson. The Higgs boson then appears, and its mass is a free parameter of the theory. In addition, the Higgs field interacts with quarks and leptons with a coupling proportional to their masses, whilst it does not couple with massless particles such as photons or gluons.

The Higgs boson has been discovered in 2012 by both ATLAS [97] and CMS [98] with a mass of 125 GeV. Its discovery is a crucial step towards a better understanding of the Standard Model, and several more studies are needed to completely characterize this particle and its interactions.

5.1.2 Higgs boson production and decay at the LHC

In LHC collisions, the Higgs boson is produced via four mechanisms: gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production with a gauge boson (VH), and associated production with a top-quark pair ($t\bar{t}H$). The plot in Figure 5.2 shows the Higgs production cross section for the various production processes as function of the Higgs mass m_h . From this plot one can notice that, given a mass of 125 GeV, the two largest production processes are ggF and VBF. The analysis, therefore, focuses only on these two production channels, whose Feynman diagrams are shown in Figure 5.3. The remaining two are described in [93].

In the ggF process, the Higgs boson is produced from a triangular diagram of virtual quarks,

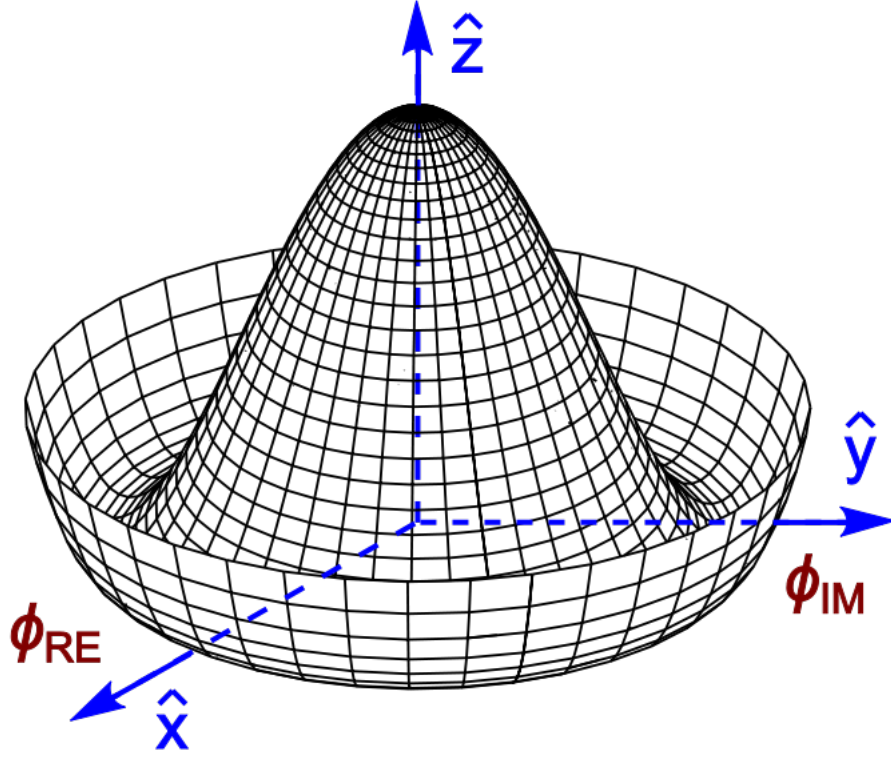


Figure 5.1: Sketch of the Higgs potential function (familiarily known as Mexican hat) [52]. The axes refer to the real and imaginary components of the Higgs field.

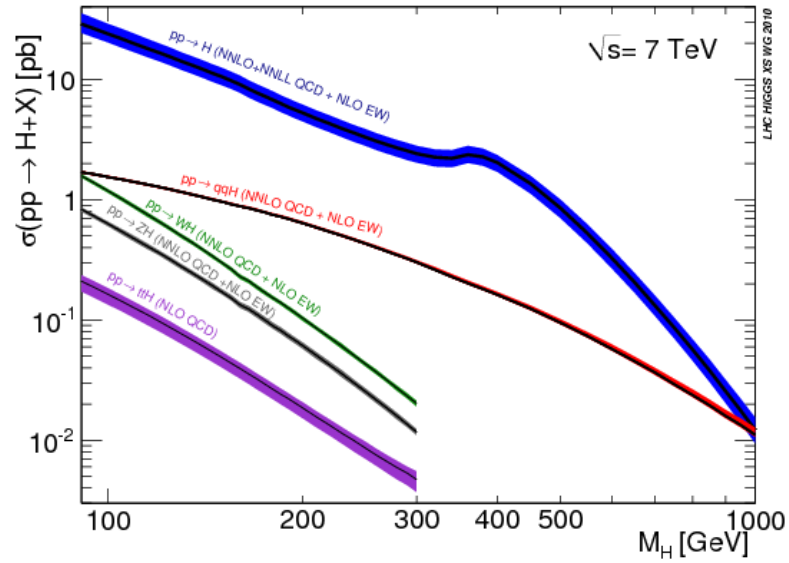


Figure 5.2: The Higgs boson production cross section as a function of its mass for different production modes at the LHC [99].

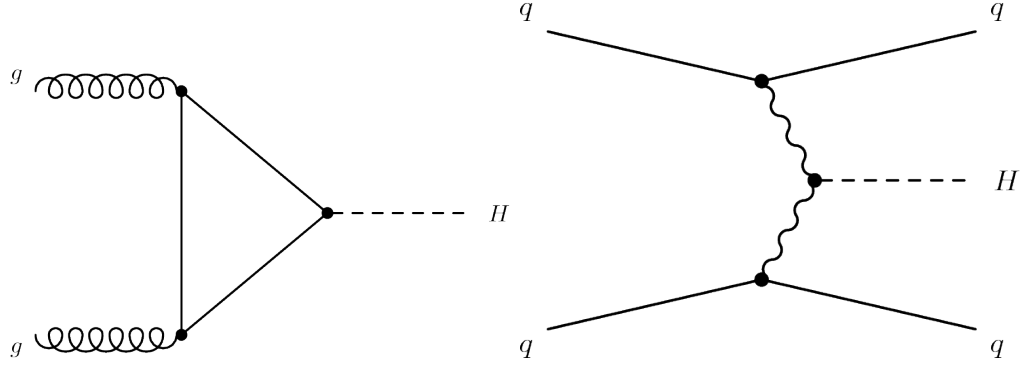


Figure 5.3: Feynman diagrams of the two largest Higgs production modes at the LHC. Left: ggF production mode (87%), right: VBF production mode (7%).

since the Higgs boson does not couple directly to gluons. Given that the Higgs boson coupling with a particle is proportional to the particle's mass, the quark triangle is dominated by top quarks, as they are the heaviest of the quarks. In computing the cross section, the top quark mass in the triangle is assumed, as an approximation, to be infinite. The cross section for this process, then, has been computed to next-to-next-leading order (NNLO) and next-to-next-to-next-leading order (N3LO) in α_s at $m_h = 125$ GeV. The next-to-leading order (NLO) corrections increase the leading order (LO) cross section computation by 80%. The NNLO, instead, increases the cross section by a further 30%. NLO Electroweak corrections increase the cross section by 5%. The recently added N3LO corrections only enhance the Higgs production by 3% [100].

The total ggF production cross section at $\sqrt{s} = 13$ TeV for a 125 GeV Higgs is:

$$\sigma_{ggF}^{N3LO} = 48.6_{-3.3}^{+2.2}(\text{theory}) \pm 1.6\text{pb}(\text{PDF} + \alpha_s). \quad (5.1)$$

and it makes up 87% for the total Higgs production cross section [101].

The VBF process is based on the scattering of two initial state quarks mediated by the exchange of W or Z bosons. In this process the Higgs is produced by the interaction between the weak bosons. After exchanging the weak bosons, the two initial state quarks are scattered at small angles from the beam axis (i.e. high η), and therefore are recorded by the detector as two highly energetic jets. This particular topological feature is very helpful for selecting VBF events.

Since the exchange of the W/Z boson is governed by the weak interaction, the VBF production cross section is much smaller than the ggF. It has been computed to be 3.748 pb^{-1} for $m_h = 125$ GeV at $\sqrt{s} = 13$ TeV, accounting for only 7% of the total cross section.

After being produced, the Higgs boson quickly decays to particles with smaller masses. Since the Higgs couplings to fermions and bosons are proportional to the particle masses, the Higgs

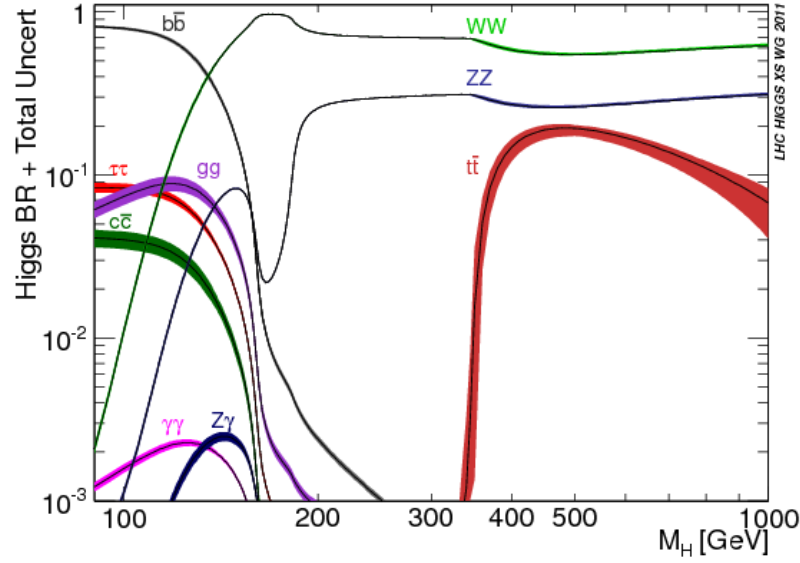


Figure 5.4: The Higgs branching fractions as a function of the Higgs mass [99].

boson tends to decay into the heaviest particles which are allowed by the available phase space. The relative probability for a particle to decay to a certain set of particles with respect to the total range of decay modes is quantified by the *branching fraction*. The branching fraction for each of the Higgs decay modes, as predicted by the SM, depends on m_h , as shown in Figure 5.4. From this plot, one can notice that at $m_h = 125$ GeV, a wide range of decay modes is available to the Higgs boson. The decay mode with the highest branching fraction is the $H \rightarrow b\bar{b}$, which accounts for about 58% of the decays. The second largest decay mode is $H \rightarrow WW$, which makes up 21% of the total branching ratio. The rest is shared between $H \rightarrow \tau^+\tau^-$ (6%), $H \rightarrow ZZ$ (3%), $H \rightarrow \gamma\gamma$ (0.23%), and others [99].

For the discovery of the Higgs boson, the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay modes were used, since they provide the cleanest signal measurement against a much larger background. The total decay width of the Higgs, Γ_h , is the sum of the widths of all the decay modes, and it depends on m_h . In the SM, the Higgs at 125 GeV, has a small total decay width of $\Gamma_h = 4.07$ MeV.

5.2 Analysis motivation

The $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis is a multi-purpose analysis, since it investigates the properties of the SM Higgs boson, as well as setting limits for non-SM processes [102]. The searches for particles not observed in the detector is the main subject of the next chapter, and it will be shown first in this section. Later, other investigations in the $\ell\ell\nu\nu$ framework will be shown, such as a search for a higher mass Higgs boson and a SM Higgs boson off-shell analysis.

5.2.1 Searches for invisible particles

The signature of the $\ell\ell\nu\nu$ final state (two opposite charge leptons and a large missing energy, E_T^{miss}) is common also to a series of non-SM processes involving the decay of the Higgs boson into invisible particles [103]. The term invisible refers to the fact that they are not detected by the experiment's subsystems, and they therefore will constitute the E_T^{miss} .

Some Beyond Standard Model theories, for instance, predict the Higgs boson decay into two particles with very small interaction cross sections with SM particles, such as neutralinos [104, 105], graviscalars in extra-dimension theories [106, 107], Majorons [108, 109] and Dark Matter through the Higgs portal model [110, 111]. In addition, some cosmological models state that the Dark Matter consists of weakly interacting massive particles (WIMPs) [112], and some non-SM theories, on the other hand, allow the Higgs boson to decay into WIMPs. Thus, the study of the branching ratio of the Higgs boson to invisible particles is a unique way to investigate Dark Matter.

In all these cases, the $\ell\ell\nu\nu$ analysis is sensitive to the invisible decay of a Higgs boson produced in association with a Z boson, where the Z boson decays into a pair of leptons. The E_T^{miss} , then, will be produced by the invisible decay of the Higgs boson. Typically, for these Beyond Standard Model events, the E_T^{miss} is larger than for the background events. The observed E_T^{miss} distribution, therefore, is compared with the SM predictions, and if no deviation is found, the results can be used to constrain the existence of new physics. As a result, the upper limit on the branching ratio of Higgs to invisible (with $m_H = 125$ GeV) can be derived assuming the SM ZH production cross-section [113]. The leading order Feynman diagram of the Higgs boson production associated with a Z boson can be seen in Figure 5.5(a).

Finally, the analysis can be sensitive even to processes where the Higgs boson is not produced at all, i.e. where invisible particles are directly produced in association with a single Z boson. This analysis, therefore, is sensitive to those events where the Z boson decays into a pair of leptons, while the invisible particles will constitute the E_T^{miss} . For this reason, this channel is commonly referred to as mono- Z . The leading order Feynman diagram for mono- Z production with invisible particles can be seen in Figure 5.5(b).

Having very similar characteristics, the Higgs to invisible and mono- Z analysis channels are grouped together under the name of “low mass” analysis. In these cases, the main goal of the analysis mode is the search for invisible particles. In this case the Z boson is not produced from the Higgs decay, and therefore the discriminating variable is the E_T^{miss} alone. The work

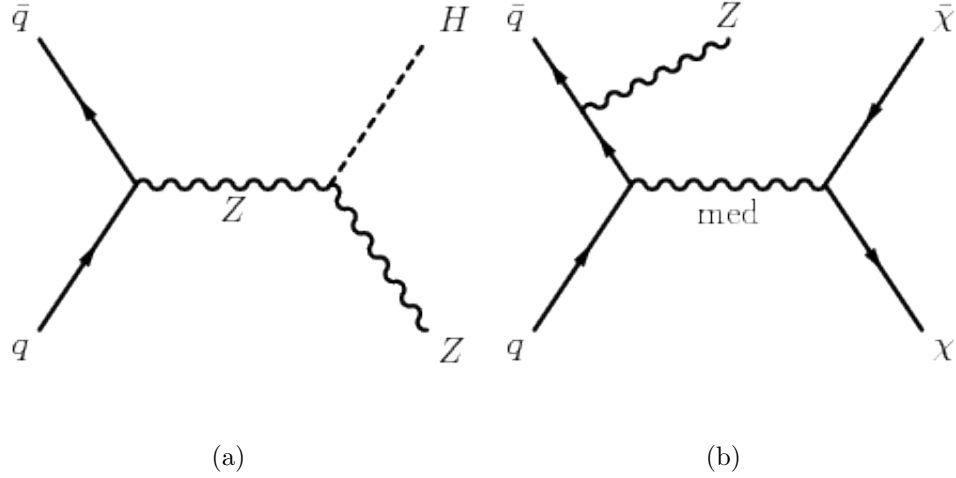


Figure 5.5: (a) Feynman diagram at the leading order for ZH production, with H eventually decaying to invisible particles, and (b) for mono- Z production associated to a pair of invisible particles [113].

of this thesis, shown in the next chapter, is aimed to improve the results of the searches for invisible particles in the $\ell\ell\nu\nu$ analysis.

5.2.2 Higher mass Higgs bosons

Furthermore, the $\ell\ell\nu\nu$ analysis can investigate the possibility for a high mass Higgs boson [114]. The new heavy Higgs that the analysis aims to find would have similar properties to the Standard Model Higgs. It would be an electrically neutral CP-even scalar particle. It would also be produced via the ggF and VBF mechanisms. If this new Higgs boson has a mass greater than twice the mass of the Z boson, it will decay to two on-shell Z bosons with a high branching fraction (see Figure 5.4). Therefore, the $\ell\ell\nu\nu$ analysis will play an important role in discovering and studying this new Higgs boson.

An important feature of the SM Higgs boson is that its width is proportional to the cube of its mass. In the case of a heavy Higgs boson, therefore, the width would be very large and the peak would be practically undetectable. In this analysis, instead, the width of the heavy Higgs is assumed to be negligible. This is the so-called narrow-width-approximation (NWA).

For this kind of search, the discriminating variable between signal and background processes is the transverse mass of the ZZ system, m_T^{ZZ} , defined as:

$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + |\mathbf{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\mathbf{E}_T^{\text{miss}}|^2} \right]^2 - [\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}]^2} \quad (5.2)$$

where m_Z is the nominal value of the mass of the Z boson (91.2 GeV [101]) and $\mathbf{p}_T^Z = \mathbf{p}_T^{\ell\ell}$, i.e. the vectorial sum of the two leptons' p_T . The m_T^{ZZ} variable is a proxy of m_{ZZ} , since the momenta of the individual neutrinos are unknown and therefore m_{ZZ} can not be measured directly.

5.2.3 Standard Model Higgs boson off-shell analysis

As regards the SM processes, the $\ell\ell\nu\nu$ analysis is sensitive to the off-peak regions of the $H \rightarrow ZZ$ process, with invariant mass above $2 \times m_Z$, through off-shell and background interference effects [115]. This feature provides a way of investigating the off-shell signal strength and the associated off-shell couplings of the Higgs boson. This aspect of the analysis, therefore, is valuable for confirming the SM predictions, as well as for setting limits to beyond SM theories.

5.3 Analysis objects

In this section, the various objects used in the analysis will be described. The objects are the final products of the interactions between the particles coming out of the collisions and the sub-detectors in the experiment. Understanding the way the objects are produced, therefore, is essential for reconstructing them adequately and reproducing the event with high accuracy. The objects considered by the $\ell\ell\nu\nu$ analysis are the electrons, the muons, the jets and the missing energy.

5.3.1 Electrons

Electrons are reconstructed by combining the information extracted from the Inner Detector and the Electromagnetic Calorimeter. Electron reconstruction is performed in three steps [116]. The first step is to look for deposits in the Electromagnetic Calorimeter, called electron “seeds”, the second is to reconstruct the tracks in the Inner Detector and the third is to associate the seeds with the tracks.

Further algorithms are applied to the reconstructed electrons to identify their origin. These methods are likelihood-based (LH), and are aimed to discriminate electrons coming from the primary vertex from those coming from photon conversions, hadronic jets or semileptonic hadron decays. The output of these algorithms is an id tag depending on the minimum likelihood value required. Every id tag has a certain signal acceptance efficiency and back-

ground rejection efficiency [117]. For instance, the “medium” id criteria have a 90% signal acceptance efficiency for electrons with $E_T \approx 40$ GeV and improve at higher energy. Another set of criteria to identify electrons produced by secondary sources is the isolation. In this case, a conical volume of a certain ΔR (as defined in Section 1.3.1) is investigated around either the track or the calorimeter deposit, and an algorithm identifies residual clusters inside this cone. Like the id criteria, the output of this algorithm is a tag, called an isolation tag. In this case, this tag depends on the amount of residual clusters around the object. For instance, the “Loose” operating point has a flat 99% efficiency for both calorimeter and track isolation.

5.3.2 Muons

Muons are reconstructed from the combinations of the tracks extracted from the Inner Detector and the tracks in the Muon Spectrometer [118]. First, the tracks are reconstructed separately in the two subsystems, then the tracks from the spectrometer are extrapolated and matched with the ones in the Inner Tracker.

Like electrons, muons are tagged based on identification criteria, which discriminate those coming from the hard scatter interaction from the ones coming from secondary processes.

Another similarity with electrons is the fact that muons can be classified depending on their isolation. In this case, specific algorithms investigate deposits in a cone around the track in the Inner Detector and the Electromagnetic Calorimeter.

5.3.3 Jets

Jets are the result of the hadronization of quarks and gluons coming out of the LHC collisions. When the quarks and gluons emerge from the interaction point, they produce collimated groups of hadrons and interact with the detectors. These hadrons are then clustered into jets. The definition of a jet is not unique, but depends on the algorithm used to merge the contributions from the different sections of the detector.

In general, to reconstruct a jet, a group of neighbouring calorimeter cells with energy significantly above the noise levels is located, which will then constitute a topological cell cluster [119]. In this analysis, the jets are constructed with the anti- k_t sequential recombination algorithm [120] setting a radius parameter, R , of 0.4. This algorithm is widely used in the ATLAS collaboration. Given any two constituents of the jet, i.e. the single calorimeter energy deposits, the procedure starts by defining their distance as

$$d_{ij} = \min \left(\frac{1}{k_{t,i}^2}, \frac{1}{k_{t,j}^2} \right) \left(\frac{\Delta_{ij}}{R} \right)^2 \quad (5.3)$$

where $k_{t,i}$ is the transverse momentum of the i th constituent of the jet and $\Delta_{ij}^2 = (\Delta y_{ij})^2 + (\Delta\phi_{ij})^2$ is the sum of squares of the difference in rapidities (Δy) and difference in azimuthal angle ($\Delta\phi$). Along with d_{ij} , a beam distance is defined for each constituent as

$$d_{iB} = 1/k_{t,i}^2. \quad (5.4)$$

The algorithm then finds the minimum of the d_{ij} and d_{iB} values. If the minimum is d_{ij} , then i and j are clustered together by summing their four-momenta and all distances are recalculated. If instead the d_{iB} is lower than d_{ij} , the system is defined as a jet. After jets are reconstructed, a calibration is performed to accurately calculate their four-momentum and resolution [121, 122].

Like for electrons and muons, jets are then tagged by specific algorithms to identify them as soft pile-up jets or hard-scatter jets. The algorithm used in the $\ell\ell\nu\nu$ analysis is the Jet Vertex Tagger (JVT), a likelihood method based on a multivariate analysis (MVA) technique. The output of this method is a value ranging between 0 (for a soft pile-up jet) and 1 (for a hard-scatter jet).

Furthermore, additional quality criteria are used [123]. These criteria inspect calorimeter variables to discriminate detector noise, beam induced background and cosmic-ray showers [124].

In addition, depending the kinematic configuration, jets can be discriminated based on the flavour of the original quark. In particular, the b -quarks live long enough to travel some distance away from the interaction vertex before decaying into jets. In this case, the pixel detector in the Inner Tracker is accurate enough to distinguish the decay vertex from the interaction vertex. This ability provides an effective b -jet identification method, called b -jet tagging, or simply b -tagging [125]. The b -tagging algorithms are various and can be combined together in a boosted decision tree to obtain a discriminant variable. In the analysis a threshold is set to this variable to efficiently tag a b -jet from a “light” flavour jet.

5.3.4 Missing energy

The collisions in the LHC can produce many “invisible” particles, i.e. particles that are not detected by the experiment subsystems. Typically these particles are neutrinos, but there can be other non-SM particles which can pass through the detectors without releasing any signal. Since the momentum vectors of all the interaction products sum to zero in the transverse plane, these invisible particles are seen as an imbalance of the total momentum computation. This imbalance is called missing transverse energy, E_T^{miss} ($\mathbf{E}_T^{\text{miss}}$ when used in the form of a vector) [126].

The $\mathbf{E}_T^{\text{miss}}$ is formed by two contributions:

$$\mathbf{E}_T^{\text{miss}} = \mathbf{E}_T^{\text{miss}}(\text{hard}) + \mathbf{E}_T^{\text{miss}}(\text{soft}) \quad (5.5)$$

where the $\mathbf{E}_T^{\text{miss}}(\text{hard})$ is obtained from the sum of the momenta of all the measured and calibrated physics objects, while the $\mathbf{E}_T^{\text{miss}}(\text{soft})$ term is obtained from unassociated tracks [127]. This last term is known as Track-based Soft Term (TST), and takes into account hadronic jet recoils from low energy interactions.

5.4 Analysis strategy

The signature of the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis is a large E_T^{miss} and two energetic leptons, either electrons or muons. For ease of reference, when focusing on electrons only we talk about the ee channel, when focusing on muons only we refer to this channel as $\mu\mu$ (or mm). In the LHC collisions there are many processes that can mimic the same signature as the $\ell\ell\nu\nu$ signal. The events produced by these processes will constitute the analysis backgrounds, as explained later in Section 5.5. The search strategy is aimed to enhance the sensitivity to the signal of interest.

The analysis strategy consists of three selection stages: object selection (5.4.1), event pre-selection (5.4.2) and event selection (5.4.3). In the first stage, the object selection, quality criteria are applied to the reconstructed objects, i.e. electrons, muons, jets and E_T^{miss} . Later, the event pre-selection removes spurious events in data, such as those containing erroneous detector effects. The final step is the event selection, where the kinematic characteristics of the event are used to set a series of cuts. These cuts are aimed at retaining signal while removing background events.

The selections described so far are common to both Higgs production modes. The two modes can be separated later by applying selections on the topology of the leading and sub-leading jet systems. Events which pass these requirements are classified into the VBF signal region (Section 5.4.4), while events which fail them are placed into the ggF signal region (Section 5.4.5).

5.4.1 Object Selection

The first step of the analysis is the object selection. During this process, in each event the objects that do not meet specific quality criteria are removed from the event. This procedure is aimed to ensure that the events are reconstructed with the highest accuracy possible.

Table 5.1 summarises all the criteria applied to the analysis objects. For ease of reference, the two leading p_T leptons which pass all object selections are classified as “signal”, while any third lepton is classified as “veto”.

5.4.1.1 Electrons

As for the electrons, requirements on p_T and η are first applied to ensure an efficient detector reconstruction. More specifically, p_T is required to be higher than 7 GeV and $|\eta|$ lower than 2.47. Later, electrons with “loose” id are rejected, leaving only electrons with at least the “medium” quality tag. Selections on the impact parameters, d_0 and z_0 , are also implemented. d_0 and z_0 are the distances of the track vertex from the interaction vertex in the transverse plane and on the beam axis respectively. These selections, therefore, are aimed to remove electrons from photon conversions in the tracker or produced from secondary vertexes. More specifically, events with a large d_0 significance (d_0/σ_{d_0}) are removed, while a maximum value is set for $z_0 \cdot \sin(\theta)$, where θ is the polar angle of the track with respect to the beam line axis. “Loose” isolation criteria are required. In addition, electrons are required to have a minimal angular separation with muons and jets, to avoid overlaps between them. A procedure named Overlap Removal (OR) is therefore performed, in which an electron is removed if found within a ΔR of 0.2 from any muon or jet. As a last selection, the two signal electrons are required to have a minimum E_T of 20 GeV and to have a “Medium” id tag, while the veto electrons have less restrictive constraints ($E_T > 7$ GeV and “Loose” id).

5.4.1.2 Muons

The selections for muons are very similar to the ones for electrons. Restrictions on the p_T and η are implemented ($p_T > 7$ GeV and $|\eta| < 2.5$), followed by requirements on the track quality. In addition, $|d_0/\sigma_{d_0}|$ is required to be lower than 3 and $|z_0 \cdot \sin(\theta)|$ lower than 0.5 mm. Muons are also required to have “Loose” isolation. An Overlap Removal procedure is applied between muons and jets with a ΔR parameter above 0.2. Like for the electrons, a p_T cut is applied to the muons, and the value of this cut is different for the two signal muons ($p_T > 20$ GeV and “Medium” id) with respect to the veto ones ($p_T > 7$ GeV and “Loose” id).

5.4.1.3 Jets

After reconstruction, jets undergo specific object selections. Like electrons and muons, requirements on p_T and η are imposed ($p_T > 20$ GeV and $|\eta| < 4.5$). A minimum JVT output value (see Section 5.3.3) of 0.59 is required to jets with $p_T < 60$ GeV and $|\eta| < 2.4$ to suppress pile-up contributions. Overlap removal is performed to remove muons if the ΔR between the jet and muon is less than 0.4. The last jet selection is a quality id requirement (“LooseBad”) to remove jets whose reconstruction may be affected by detector inefficiencies.

5.4.1.4 Missing energy

The E_T^{miss} is built before all object selections from the electrons, muons and jets in the event. The requirements on these objects, though, are different from the ones applied later during the object selection. The electrons that contribute to the E_T^{miss} computation are required to have “Loose” quality criteria and a p_T greater than 10 GeV. Electrons are required to have $|\eta| < 2.47$, which corresponds to the edges of the tracker. Similarly, muons are required to have “Loose” quality criteria, a p_T greater than 20 GeV and $|\eta|$ lower than 2.5. The requirements for jets are the same as for the object selection. As explained in Section 5.3.4, the soft term is reconstructed from the Inner Detector.

5.4.2 Event Pre-Selection

The second step of the analysis strategy is the event pre-selection.

While taking data, the detector can suffer from malfunctions and therefore collect spurious or incomplete events. For this reason, ATLAS provides a Good Run List (GRL), a list of events where the detector was working properly. In the analysis pre-selection, therefore, the events are required to belong to a GRL. This ensures that the data are reconstructed with the best performance of the detector.

In addition, all events are required to be fully reconstructed by the detector, in order to discard poorly reconstructed events due to detector mis-measurements. For instance, events with good hits in the SCT are selected, to ensure that they are not affected by problems in the SCT read-out. Moreover, LAr and Tile quality flags are checked in order to avoid noise bursts and data corruption. Events are also required to contain a primary vertex, i.e. a hard-scatter vertex with the largest $\sum p_T^2$ with at least two outgoing associated tracks.

Another set of pre-selection cuts is based on jet quality. Low quality jets, in fact, may give rise to large fake E_T^{miss} , which can result in a poor description of the tail of the E_T^{miss} distribution. These low quality jets typically originate from non-collision events, such as hardware problems, cosmic-ray showers or beam-related backgrounds. To remove these jets from the successive analysis steps, events which do not pass the loose jet quality selections are rejected [128].

The event pre-selection cuts are summarised in Table 5.2.

5.4.3 Event selection

The cuts applied so far have set requirements on the quality of the data, with no discrimination between signal and background. This is done in the last step of the selections, the

Object	Object Selection
Electrons	$p_T > 7 \text{ GeV}, \eta < 2.47$ “Medium” object quality condition $ d_0/\sigma_{d_0} < 5$ and $ z_0 \cdot \sin(\theta) < 0.5 \text{ mm}$ “Loose” isolation criteria Overlap Removal between e and μ and between e and jets Signal (veto) e has $E_T > 20$ (7) GeV and LH “Medium” (“Loose”)
Muons	$p_T > 7 \text{ GeV}, \eta < 2.5$ Reconstructed using combined algorithm $ d_0/\sigma_{d_0} < 3$ and $ z_0 \cdot \sin(\theta) < 0.5 \text{ mm}$ “Loose” isolation criteria Overlap Removal between μ and jets Signal (veto) μ has $p_T > 20$ (7) GeV and “Medium” (“Loose”) id criteria
Jets	$p_T > 20 \text{ GeV}, \eta < 4.5$ $\text{JVT} > 0.59$ (jets with $p_T < 60 \text{ GeV}, \eta < 2.4$) Overlap Removal between jets and μ “LooseBad” quality criteria
E_T^{miss}	“Loose” e and μ “Loose” jets ($p_T > 20 \text{ GeV}$ and $\text{JVT} > 0.59$ for $p_T < 60 \text{ GeV}, \eta < 2.4$) Soft term built from tracks in ID

Table 5.1: Summary of object selections used in the $\ell\ell\nu\nu$ analysis.

Required to be in the GRL.
Not flagged as being incomplete.
SCT error requirement i.e. SCT hits are recorded.
LAr and Tile error requirements
Required to have at least one hard-scattering vertex with at least two associated tracks.
Pass “Loose” jet quality criteria.

Table 5.2: Summary of event pre-selections used in the $\ell\ell\nu\nu$ analysis.

event selection, where specific kinematic requirements are set on the final state in order to isolate signal events from the various background processes.

Events are required to contain at least two opposite-charge leptons of the same flavour which satisfy the medium id criteria. In addition, events with a third lepton are vetoed in order to suppress WZ events where the Z boson decays into a pair of leptons and the W boson decays into a lepton and a neutrino. The lepton with the highest value of p_T , named leading lepton, is required to have a transverse momentum greater than 30 GeV. These initial cuts are set to have the cleanest signal possible.

Furthermore, to select events which contain a Z boson, a cut is imposed on the invariant mass of the lepton pair, $m_{\ell\ell}$. More specifically, $m_{\ell\ell}$ is selected to be within 15 GeV of m_Z , where m_Z is equal to 91.187 GeV. This condition therefore reduces the backgrounds that contain no Z bosons.

Since the signal signature has a pair of neutrinos in the final state, a large E_T^{miss} cut is also applied. In this case the cut value depends on the specific goals of the analysis. It is set to 90 GeV if looking for invisible particles, 120 GeV if looking for high mass Higgs bosons or 150 GeV if looking for Higgs bosons produced off-shell.

Another kinematic cut regards the lepton directions. Since the leptons are produced from a Z boson with non-zero transverse momentum, they are expected to be directed very close to each other. Therefore, the two leptons are required to have $\Delta R_{\ell\ell} < 1.8$, where $\Delta R_{\ell\ell}$ is the Lorentz-invariant angular separation, defined by

$$\Delta R_{\ell\ell} = \sqrt{\Delta\eta_{\ell\ell}^2 + \Delta\phi_{\ell\ell}^2} . \quad (5.6)$$

Furthermore, in the transverse plane the two Z bosons are produced from a Higgs boson at rest, and therefore they move in opposite directions. This means that the angular separation between the di-lepton system and E_T^{miss} is expected to be very large. For this reason, a cut is

applied on the azimuthal angle between the lepton pair and E_T^{miss} , $\Delta\phi(p_T^Z, E_T^{\text{miss}})$, which must be greater than 2.7. This condition suppresses backgrounds with less than two Z bosons. Another kinematic property is analyzed. The reconstructed Z boson can be expected to recoil against the $\mathbf{E}_T^{\text{miss}}$. In this case, imbalances in the recoil are quantified by the fractional p_T , defined as $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$. In this definition, $E_T^{\text{miss,jet}}$ is a variable that takes into account both E_T^{miss} and the vectorial sum of the transverse momentum of jets, i.e. $E_T^{\text{miss,jet}} = |\mathbf{E}_T^{\text{miss}} + \Sigma \mathbf{p}_T(\text{jet})|$. In the event selection, the fractional p_T is required to be less than 0.2.

In addition, a cut is applied to suppress the contributions of mis-measured jets in the E_T^{miss} direction, which is a prominent feature of some backgrounds. For this purpose, a requirement is applied on the minimum distance between any jet with p_T greater than 100 GeV and E_T^{miss} , $\Delta\phi(p_T^{\text{jet}} > 100 \text{ GeV}, E_T^{\text{miss}})$. This variable is required to be greater than 0.4.

Another cut is aimed to remove spurious jet contaminations. This cut is applied to the E_T^{miss}/H_T variable, where H_T is defined as the scalar sum of the transverse momenta of the jets and leptons. Some backgrounds tend to have a large H_T without a correspondingly large E_T^{miss} and thus cluster at low E_T^{miss}/H_T . A threshold value of 0.4 was found to be optimal. To reduce the contamination from backgrounds with b -jets (i.e. jets originated from a b quark), a veto on any b -tagged jets is applied. For the b -tagging of the jets, the multivariate algorithm output, MV2c10 [125], is applied, and a jet is considered b -tagged if the MV2c10 output has a value greater than 0.1758. In the $t\bar{t}$ samples, this value provides a 85% efficiency working point in correctly tagging a b -jet, while the mistag rate (the fraction of mis-tagged jets) is lower than 10%.

A summary of all applied analysis selections is provided in Table 5.3. The selections discussed so far are applied to both the Higgs production channels considered by the analysis. The next two sections will show the procedure to classify events related to the VBF and ggF production channels respectively.

5.4.4 VBF selections

The VBF classification procedure relies on tight selections on the leading and sub-leading jets, i.e. the jets with the highest and second highest p_T . The number of jets, N_{jets} must be at least 2. The di-jet system that characterizes the VBF topology is formed by the leading and sub-leading jets. All jets are required to have a p_T greater than 30 GeV and the invariant mass of the di-jet system, m_{jj} is required to be greater than 550 GeV. The last important feature that defines the VBF selections is the difference between jet pseudorapidities:

$$|\Delta\eta_{jj}| = |\eta_{j_1} - \eta_{j_2}| . \quad (5.7)$$

Event should contain a same-flavor, opposite-charge lepton pair (muons or electrons).
$p_T^{\ell, \text{leading}} > 30 \text{ GeV}, p_T^{\ell, \text{sub-leading}} > 20 \text{ GeV}$
No additional 'veto' leptons are required (with $p_T > 7 \text{ GeV}$)
$ m_Z - m_{\ell\ell} < 15 \text{ GeV}$
$E_T^{\text{miss}} > 120 \text{ GeV}.$
$\Delta R_{\ell\ell} < 1.8$
The $\Delta\phi(p_T^Z, E_T^{\text{miss}}) > 2.7$
Minimal $\Delta\phi(p_T^{\text{jet}} > 100 \text{ GeV}, E_T^{\text{miss}}) > 0.4$
$ E_T^{\text{miss, jet}} - p_T^{\ell\ell} /p_T^{\ell\ell} < 0.2.$
$E_T^{\text{miss}}/H_T > 0.4$, where $H_T = \sum p_T^{\text{lep}} + \sum p_T^{\text{jet}}$
No b -tagged jets

Table 5.3: Summary of the event selection used in the $\ell\ell\nu\nu$ analysis.

Require a cut on the number of jets, $N_{\text{jets}} \geq 2$.
Minimum jet p_T requirement, $p_T^{\text{jet}} > 30 \text{ GeV}$
Di-jet mass selections, $m_{jj} > 550 \text{ GeV}$
Di-jet pseudorapidity separation, $ \Delta\eta_{jj} > 4.4$

Table 5.4: Summary of VBF events selections used in the $\ell\ell\nu\nu$ analysis.

A large value of $|\Delta\eta_{jj}|$ ensures that the jets are in the forward parts of the calorimeter. The $|\Delta\eta_{jj}|$ is thus required to be greater than 4.4.

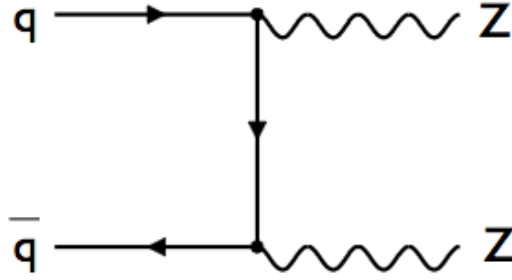
The selections are summarized in Table 5.4.

5.4.5 ggF selections

The ggF signal region is defined to avoid overlap with the VBF signal region. Thus the ggF phase space consists of events passing all the event selections and failing one or more VBF selections.

The cuts to isolate the ggF topology are given in Table 5.5.

All $H \rightarrow ZZ \rightarrow \ell\nu\nu$ event selections applied.
Any events which fail any one of VBF requirements is added to ggF region.

Table 5.5: Summary of ggF events selections used in the $\ell\nu\nu$ analysis.Figure 5.6: Feynman diagram for the production of the irreducible $qq \rightarrow ZZ$ background.

5.5 Analysis backgrounds

In this section the main background sources for the analysis will be described, along with the methods used to estimate their yields.

5.5.1 ZZ background

The largest source of background in the $\ell\nu\nu$ analysis is given by events produced in the ZZ processes, both from quark-quark and gluon-gluon interactions. The Feynman diagrams for the ZZ events in the quark-quark and gluon-gluon production modes are shown in Figures 5.6 and 5.7 respectively. In the LHC collisions, Z pairs are produced in non-resonant states. Afterwards, if one of the two Z decays to leptons and the other to neutrinos, the event contains the same final state particles as the $\ell\nu\nu$ signal. For this reason, this background is considered “irreducible”.

In both the ggF and VBF signal regions, the ZZ background is modelled using MC simulation. For the $qq \rightarrow ZZ$ process the **Powheg** + **Pythia8** generator is used [129]. The $gg \rightarrow ZZ$ process, instead, is simulated by the **GG2VV** generator [115, 130]. In the VBF category, a **SHERPA** NNLO sample is also used [131].

In the $\ell\nu\nu$ analysis, the ZZ background accounts for $60 \pm 3\%$ of background events from Monte Carlo [102].

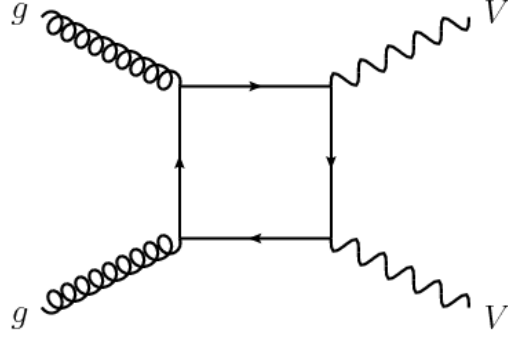


Figure 5.7: Feynman diagram for the production of the irreducible $gg \rightarrow ZZ$ background.

5.5.2 WZ background

WZ events are the second largest background source in the $\ell\ell\nu\nu$ analysis. When a W and a Z boson are produced in a non-resonant state, the Z boson can decay into two leptons and the W boson in a lepton and a neutrino. Although this is not the same final state as the $\ell\ell\nu\nu$, one of the leptons may be mis-reconstructed, leading the event to enter the $\ell\ell\nu\nu$ signal region.

In estimating the yield of this background, the **Powheg** + **Pythia8** generator [129] is used to model the variables and a data-driven method is used to obtain scale factors as follows. The data-driven method consists of data/MC comparisons in a three-lepton control region, which is dominated by $WZ \rightarrow \ell\nu\ell^+\ell^-$ events. This control region is obtained by removing the third lepton veto in the event selections. The scale factor is calculated from the observed data/MC difference in the control region, and then applied to the WZ simulation in the signal region. The yield in the signal region is found by:

$$N_{2\ell,\text{SR}}^{\text{data}} = N_{2\ell,\text{SR}}^{\text{MC}} \times \left(\frac{N_{3\ell,\text{CR}}^{\text{data}}}{N_{3\ell,\text{CR}}^{\text{MC}}} \right) = N_{3\ell,\text{CR}}^{\text{data}} \times \left(\frac{N_{2\ell,\text{SR}}^{\text{MC}}}{N_{3\ell,\text{CR}}^{\text{MC}}} \right) \quad (5.8)$$

where $N_{2\ell,\text{SR}}^{\text{data}}$ is the number of events in the data in the $\ell\ell\nu\nu$ signal region and the scale factor is defined as

$$\text{SF} = N_{3\ell,\text{CR}}^{\text{data}} / N_{3\ell,\text{CR}}^{\text{MC}} \quad (5.9)$$

In the $\ell\ell\nu\nu$ analysis, the WZ background accounts for the $21 \pm 2\%$ of background events [102].

5.5.3 WW , $t\bar{t}$, Wt , $Z \rightarrow \tau\tau$ background

Another set of background events is related to WW , $t\bar{t}$, Wt and $Z \rightarrow \tau\tau$ processes. These processes are grouped together because, although their final state consists of two leptons and

a large E_T^{miss} , the pair of leptons can be either ee , $\mu\mu$, or $e\mu$, with a relative probability of 1:1:2 respectively. This feature is very useful to define a data-driven estimation procedure. The $e\mu$ decay mode is cut out of the $\ell\ell\nu\nu$ analysis when two leptons of the same flavour are required. The $e\mu$ events, therefore, can be used to define a control region in the yield estimation procedure. Afterwards, one can obtain the yields of WW , $t\bar{t}$, Wt and $Z \rightarrow \tau\tau$ decaying to ee ($N_{SRee}^{e\mu}$) and $\mu\mu$ ($N_{SR\mu\mu}^{e\mu}$) from:

$$\begin{cases} N_{SRee}^{e\mu} = \frac{1}{2} \times \epsilon \times N_{e\mu}^{\text{data,sub}} \\ N_{SR\mu\mu}^{e\mu} = \frac{1}{2} \times \frac{1}{\epsilon} \times N_{e\mu}^{\text{data,sub}} \end{cases} \quad (5.10)$$

where $N_{e\mu}^{\text{data,sub}}$ is the number of data events in $e\mu$ control region after subtracting the non- $e\mu$ backgrounds and ϵ is a factor which takes into account the relative reconstruction efficiency between electrons and muons.

In the $\ell\ell\nu\nu$ analysis, these backgrounds altogether account for the $8 \pm 2\%$ of background events [102].

5.5.4 W + jets background

In the W + jets processes, a W boson is produced along with jets. In this case, the final state can mimic the $\ell\ell\nu\nu$ final state if one of the jets is mis-identified as a lepton.

The method to estimate the yield of this background is based on a data-driven “fake” factor. The fake factor is defined as the ratio of the probability for a jet to pass the full lepton identification selections over the probability of a jet passing a lepton-like jet requirement. A control region is defined with events having one “good” lepton (i.e. passing all lepton selections) and one “bad” lepton (i.e. failing either the identification or isolation requirement). The estimation of the yield in the signal region is obtained by applying the fake factor to the data yield in the control region.

The W + jets background accounts for a small portion of the total background (about 1%).

5.5.5 Z + jets background

Other events that can mimic the signal final state are related to Z + jets events. In this case, only one Z boson is produced in the collision, which then decays into two leptons. The E_T^{miss} is then due only to jet mis-reconstruction and resolution. Because of the large production cross section of the $Z \rightarrow \ell\ell$ process, Z + jets is a large background before the event selections are applied. Nevertheless, low energy jets are easier to miss than the highly energetic ones. This background, therefore, is mostly suppressed by imposing a sufficiently high E_T^{miss} cut. In addition, since in this case the E_T^{miss} is not produced by a recoiling particle, the requirements on the fractional p_T difference, $\Delta\phi(\text{jet}(p_T, E_T^{\text{miss}}))$ and E_T^{miss}/H_T contribute

to the reduction of the $Z + \text{jets}$ yield.

The yield of this background is estimated with a data-driven method, the ABCD method [103]. In this method, two uncorrelated variables are chosen, on which some cuts are applied in the event selection. The cuts applied in the selections define four regions in the bi-dimensional phase space of the variables. For ease of reference, these regions are named region A, B, C and D, with the signal region being the region A. The yield of the background is then calculated in regions B, C and D, after subtracting contributions from other backgrounds. Since the two variables are uncorrelated, the yield in region A can be calculated as

$$N_A = N_C \times \frac{N_B}{N_D} \quad (5.11)$$

where N_X is the number of events in the region X ($X = A, B, C, D$).

In the case of the $Z + \text{jets}$ background, the two variables chosen for the ABCD method were $\Delta\phi(Z, E_T^{\text{miss}})$ and the fractional p_T difference. The signal region A, therefore, is defined as the region where $\Delta\phi(Z, E_T^{\text{miss}}) > 2.7$ and fractional p_T difference < 0.2 .

Although this method is very common in statistics, its implementation in the $\ell\ell\nu\nu$ analysis suffered some problems, and the method itself had to be modified to be validated. In particular, the ABCD method is used for calculating the total number of events, whilst the shapes of the distributions are reproduced with the Sherpa Monte Carlo. The Monte Carlo samples show disagreement with data and, given the small statistics, the overall method suffers from large errors (more than 50%). For this reason, a new method has been considered to estimate this background, as we will see in the next chapter.

In the $\ell\ell\nu\nu$ analysis, the $Z + \text{jets}$ background accounts for the $8 \pm 5\%$ of background events [102].

Chapter 6

$\gamma + \text{jets}$ Reweighting method for $Z + \text{jets}$ Yield Estimation

In the previous chapter the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ analysis has been described in many of its details. In particular, the various background contributions have been outlined, among which the $Z + \text{jets}$ process stands as one of the most significant. However, the method used for the estimation of its yield, the ABCD method, suffers many complications and needs some modifications to be applied (see Section 5.5.5).

The current chapter introduces another method for the estimation of the $Z + \text{jets}$ yield, the $\gamma + \text{jets}$ reweighting method, which can be used as an alternative to the current ABCD method. The first section describes the method. Afterwards, the results obtained with this method on Monte Carlo data will be presented. Because of the disagreement shown by these results, a modification of this method will be described, and the effect of this modification on the Monte Carlo estimation will be presented. Finally, further improvements will be introduced leading to an excellent description of the $Z + \text{jets}$ background.

6.1 p_T reweighting

6.1.1 Description

The method proposed in this chapter uses $\gamma + \text{jets}$ events to model $Z + \text{jets}$ events by applying a reweighting factor [132]. This reweighting factor depends on the p_T of the γ/Z boson, i.e. the component of its momentum perpendicular to the beam axis. Since the Z boson decays into a pair of leptons (either ee or $\mu\mu$), its momentum is reconstructed by the vectorial sum of the momenta of the single leptons. The method relies on the fact that, at high transverse momentum ($p_T \gg M_Z$), photon and Z production are very similar, as they are characterized by a high energetic boson recoiling against a hadronic system. Thus, the

only difference lies in the different electroweak couplings of photons and Z bosons to quarks. This affects the production rate, which can be taken into account by reweighting the p_T distribution of the $\gamma + \text{jets}$ events to match the one of the $Z + \text{jets}$ events. The measured rate of $\gamma + \text{jets}$ production after reweighting can therefore be used to accurately predict the $Z + \text{jets}$ background.

More specifically, before using this method one applies some selections on the $\gamma + \text{jets}$ events in order to reproduce the $Z + \text{jets}$ topology as closely as possible. In this case, since the event signature of $\gamma + \text{jets}$ samples is very well defined (one highly energetic photon and a system of jets), the selections for these events can be easily applied, as will be shown in the next sections.

Afterwards, the p_T distributions of both $Z + \text{jets}$ and $\gamma + \text{jets}$ are considered, and for every value of p_T the reweighting factor is calculated as

$$w_i = \frac{N_i(p_T)_{Z+jets}}{N_i(p_T)_{\gamma+jets}} \quad (6.1)$$

where $N_i(p_T)_{Z(\gamma)+jets}$ is the number of events of the i_{th} bin in the $Z(\gamma) + \text{jets}$ p_T distribution. This factor is then applied to the $\gamma + \text{jets}$ sample event by event, depending on the photon's p_T . This way, the renormalized $\gamma + \text{jets}$ p_T distribution matches the $Z + \text{jets}$ one by construction. The application of this procedure to MC events can be seen in Figure 6.1, where the distribution of p_T for $Z + \text{jets}$ and $\gamma + \text{jets}$ before and after reweighting are shown, along with the ratio of the p_T distributions between $Z + \text{jets}$ and $\gamma + \text{jets}$ after reweighting. Subsequently, since the kinematic configurations of the two processes are very similar, the distributions for the other variables are expected to match as well. For this reason, the reweighted $\gamma + \text{jets}$ samples can be used to model the $Z + \text{jets}$ distribution.

In all the distributions shown in this chapter the bin content is divided by the bin width.

6.1.2 Object Selections

As mentioned in the previous section, before applying the $\gamma + \text{jets}$ reweighting method, some selections must be applied to the objects in the events, and then to the events themselves. Similarly to the ee and $\mu\mu$ analysis channels (Section 5.4.1), the object selections impose requirements on the quality of the objects in the analysis. In the case of $\gamma + \text{jets}$, the objects in the samples are only jets and photons. The jets are treated the same way as the $\ell\ell\nu\nu$ analysis, while the photons require a separate treatment, which will be discussed in this section.

Photons are reconstructed in ATLAS as signals in the electromagnetic calorimeters which are not associated to tracks in the tracking system. Like for electrons and muons (see Section 5.3.1 and 5.3.2), in the reconstruction algorithm, some quality tags are assigned to each

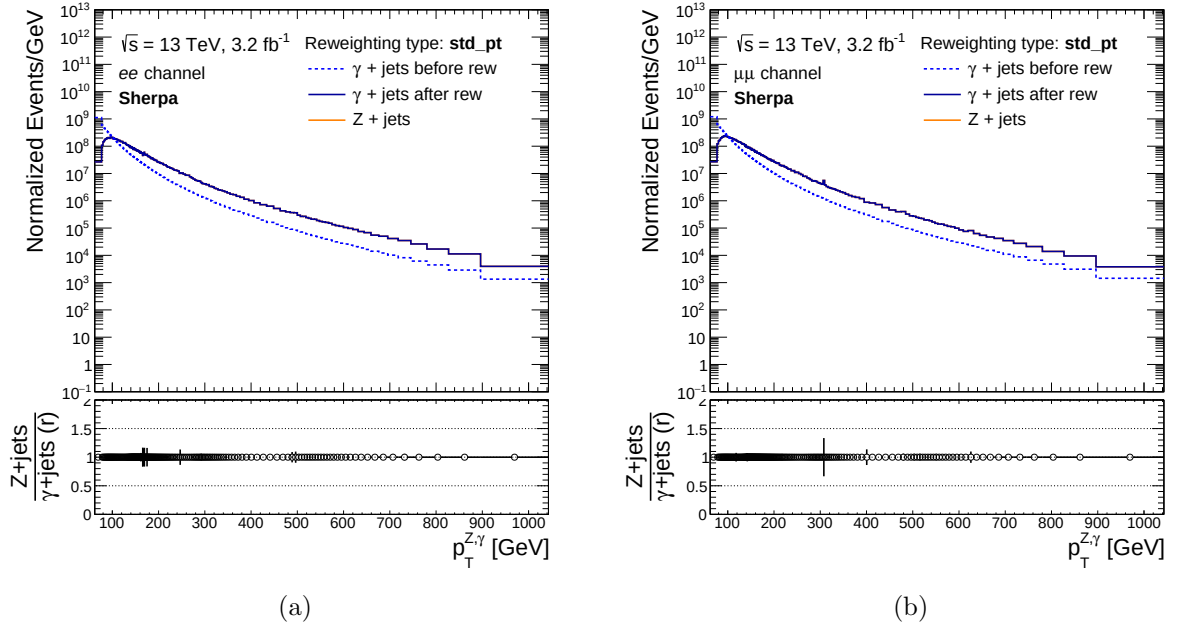


Figure 6.1: The effect of $\gamma + \text{jets}$ reweighting on the p_T distribution in the (a) ee and (b) $\mu\mu$ channels. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. In this case, the red line is overlapped by the blue line. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

photon depending on different parameters. In the object selections preceding the $\gamma + \text{jets}$ reweighting method, the first quality tag inspected is the Author tag. This tag is used to solve the ambiguity between photons coming from the interaction point and photons emitted by other objects in the event, especially electrons. In these object selections, the photons are required to be produced from hard scatters.

Furthermore, photons can undergo conversion to a lepton pair in the silicon layers of the tracking system. This analysis, specifically, uses only unconverted photons.

Like electrons and muons, photons are reconstructed with an id tag, depending on a set of cuts on several discriminating variables [133, 134]. This tag is aimed to distinguish prompt photons from background photons. For instance, the chosen “tight” id can have an identification efficiency up to $\sim 93\%$ depending on the photon’s transverse energy and pseudorapidity. A minimum p_T of 7 GeV is required to match the selection made on electrons and muons in the analysis.

To ensure an efficient detector reconstruction, a selection on the value of η is imposed. In this case, the photons with η in the range of $[1.5, 1.6]$ are vetoed as the photon response was found to be incorrect in that region [135].

In the next step of the selection, a requirement on photon isolation is imposed. Like electrons and muons, photons are classified depending on the amount of transverse energy residual

in a cone of a certain ΔR around the photon direction [136]. The transverse energy flow can be measured with the tracking system or the electromagnetic calorimeter. For $\gamma + \text{jets}$ events photons with “FixedCutTight” isolation tag are chosen, whose working point has an efficiency higher than 92% over a wide p_T range [137].

An overlap removal procedure is performed on the photons to exclude the ones emitted by jets or other objects. The overlap removal method is analogous to the one for electron and muons.

Since the analysis requires the leading lepton to have momentum higher than 20 GeV, a similar selection is applied to the $\gamma + \text{jets}$ sample.

The selections on the photons are summarized in Table 6.1.

Object	Object Selection
Photons	Author: AuthorPhoton or AuthorAmbiguous Unconverted Tight ID $p_T > 7 \text{ GeV}$ $ \eta < 1.5 \text{ or } \eta > 1.6$ FixedCutTight isolation Overlap Removal $p_T > 20 \text{ GeV}$

Table 6.1: Summary of photon selections used in the $\gamma + \text{jets}$ reweighting.

6.1.3 Event Pre-Selections

The event pre-selections used in the $\ell\ell\nu\nu$ analysis do not depend on the specific kinematic configuration of the event itself, but rather on the general detector performance at the moment of data taking (see Section 5.4.2). For this reason, the same pre-selections can be applied to the $\gamma + \text{jets}$ events.

6.1.4 Event Selections Before Reweighting

After the object selections, a set of selections is applied to the $\gamma + \text{jets}$ events in order to reproduce the topology of the $\ell\ell\nu\nu$ analysis. These selections must be treated very carefully, as the method described in this chapter relies on the fact that the $\gamma + \text{jets}$ events have a very similar kinematic configuration to the $Z + \text{jets}$ events. On the other hand, the event selections in the $\ell\ell\nu\nu$ analysis impose tight restrictions on the event kinematics themselves. It is very important, therefore, that the cuts imposed in the event selections of the $\ell\ell\nu\nu$ analysis are reproduced as close as possible in the $\gamma + \text{jets}$ event selections. For this reason, we will investigate them one by one.

Same-flavor, opposite-charge lepton pair

This cut is made to define the signal signature of the $\ell\ell\nu\nu$ channels and it can not be reproduced in the $\gamma + \text{jets}$ events. Nevertheless, it does not affect the event kinematics.

$$p_{\text{T}}^{\ell, \text{leading}} > 30 \text{ GeV}, p_{\text{T}}^{\ell, \text{sub-leading}} > 20 \text{ GeV}$$

This cut can not be reproduced on the photon p_{T} in the $\gamma + \text{jets}$ sample, as it acts separately on the two leptons produced by the decay of the Z boson. The effect can be partially accounted for by imposing the photon's p_{T} to be higher than 20 GeV in the object selections.

No additional 'veto' leptons are required (with $p_{\text{T}} > 7 \text{ GeV}$)

In the $\gamma + \text{jets}$ samples, this cut is equivalent to rejecting events with any extra lepton.

$$|m_{\text{Z}} - m_{\ell\ell}| < 15 \text{ GeV}$$

This cut can not be reproduced in the $\gamma + \text{jets}$ events, since the photon cannot decay to two leptons.

$$E_{\text{T}}^{\text{miss}} > 120 \text{ GeV}$$

This cut is applied the same way to the $\gamma + \text{jets}$ events before the reweighting procedure.

$$\Delta R_{\ell\ell} < 1.8$$

This cut can not be reproduced in the $\gamma + \text{jets}$ events, since it is related to the angular separation between the two leptons. Nevertheless, this variable is highly correlated with the p_{T} of the dilepton system ($p_{\text{T}}^{\ell\ell}$), which corresponds to the p_{T} of the Z boson, as can be seen in the bi-dimensional distribution of the two variables from MC samples (Figure 6.2(a)). The profile of this correlation (Figure 6.2(b)) shows that a value of $\Delta R_{\ell\ell}$ of 1.8 corresponds to a value of $p_{\text{T}}^{\ell\ell}$ of about 100 GeV. The effect of such a cut is to suppress the portion of the Z boson's p_{T} distribution below 100 GeV. This effect will be reflected in the reweighting

factor applied to the $\gamma + \text{jets}$ events, since this factor is directly proportional to the value of the Z boson's p_T distribution.

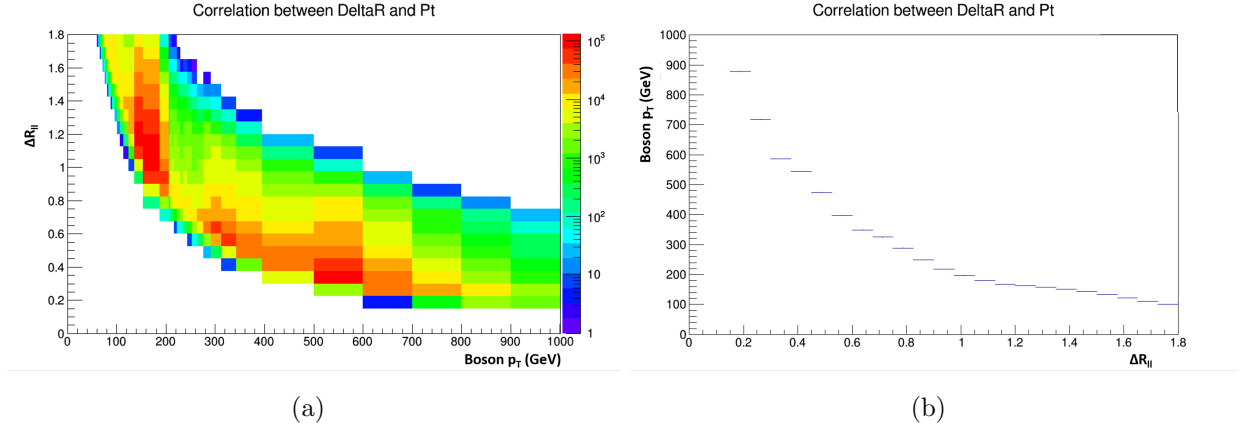


Figure 6.2: (a) 2D histogram of $p_T^{\ell\ell}$ and $\Delta R_{\ell\ell}$ from $Z + \text{jets}$ MC samples. (b) Profile of $p_T^{\ell\ell}$ as a function of $\Delta R_{\ell\ell}$ from $Z + \text{jets}$ MC samples.

Since the cut on $\Delta R_{\ell\ell}$ is the last one that does not have an equivalent for the $\gamma + \text{jets}$ sample, it has been decided to apply the p_T reweighting at this stage of the selections. The next cuts, therefore, will be applied on the reweighted samples.

6.1.5 Event Selections After Reweighting

The other remaining cuts are (in order):

- $\Delta\phi(p_T^Z, E_T^{\text{miss}}) > 2.7$ radians
- $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$
- $E_T^{\text{miss}} > 90/120/150$ GeV for Low mass/High mass/Off-shell analysis
- $E_T^{\text{miss}}/H_T > 0.4$
- No b -tagged jets

Since the $Z + \text{jets}$ background is highly suppressed for high E_T^{miss} values, the $\gamma + \text{jets}$ reweighting method has been considered in particular for the low mass searches performed in the framework of the $\ell\ell\nu\nu$ analysis. From now on, therefore, we will consider the cut on E_T^{miss} at 90 GeV only.

After the reweighting procedure is applied, the $\mathbf{p}_T$ of the photon is related to the $\mathbf{p}_T$ of the

Z boson. This means that every cut of the $\ell\ell\nu\nu$ analysis related to the Z boson's $\mathbf{p}_T$ can be reproduced with the $\gamma + \text{jets}$ samples by instead simply using the photon's $\mathbf{p}_T$. Specifically, this argument is valid for the two cuts $\Delta\phi(p_T^Z, E_T^{\text{miss}}) > 2.7$ and $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$. Furthermore, two of these cuts act on variables that are independent of the photons or leptons in the event, i.e. the E_T and the number of b -jets. These cuts, then, are applied to the $\gamma + \text{jets}$ events with no modifications from the $\ell\ell\nu\nu$ analysis.

Finally, one of these cuts is based on a variable which needs special treatment, i.e. E_T^{miss}/H_T . More specifically, the variable H_T is not reproducible with $\gamma + \text{jets}$ samples. This variable is defined in the $\ell\ell\nu\nu$ analysis as:

$$H_T = \sum_{\text{jets}} p_T^{\text{jets}} + p_T^{l1} + p_T^{l2} \quad (6.2)$$

where $p_T^{l1(2)}$ is the scalar p_T of the leading(sub-leading) lepton. This definition can not be applied to the $\gamma + \text{jets}$ samples since it features the scalar sum of the two leptons' momenta, while the photon momentum alone accounts for the vectorial sum. To overcome this discrepancy, the correlation between $p_T^{l1} + p_T^{l2}$ and $p_T^{\ell\ell}$ has been investigated with MC $Z + \text{jets}$ samples (Figure 6.3). From this correlation the profile of $p_T^{l1} + p_T^{l2}$ as a function of $p_T^{\ell\ell}$ has then been obtained (black dots in Figure 6.3). After 200 GeV $p_T^{l1} + p_T^{l2}$ tends to be equivalent to $p_T^{\ell\ell}$. This is due to the fact that at high momentum the decay products of the Z boson are very boosted and their directions are therefore collinear. Below 200 GeV, instead, the two leptons are produced with a small total momentum, and therefore there is a considerable angle between them, which deviates the scalar sum from the vectorial sum of the single momenta. The function of $p_T^{l1} + p_T^{l2}$ versus $p_T^{\ell\ell}$, which we can call $h(p_T^{\ell\ell})$, can now be applied to the p_T of the photon in the $\gamma + \text{jets}$ samples to redefine H_T :

$$H_T^\gamma = \sum_{\text{jets}} p_T^{\text{jets}} + h(p_T^\gamma) \quad (6.3)$$

where p_T^γ is the photon's p_T . Thus, the newly-defined H_T^γ variable is equivalent to the H_T variable used in the $\ell\ell\nu\nu$ analysis. In the rest of this chapter the superscript γ will be dropped when considering the H_T variable in the $\gamma + \text{jets}$ sample.

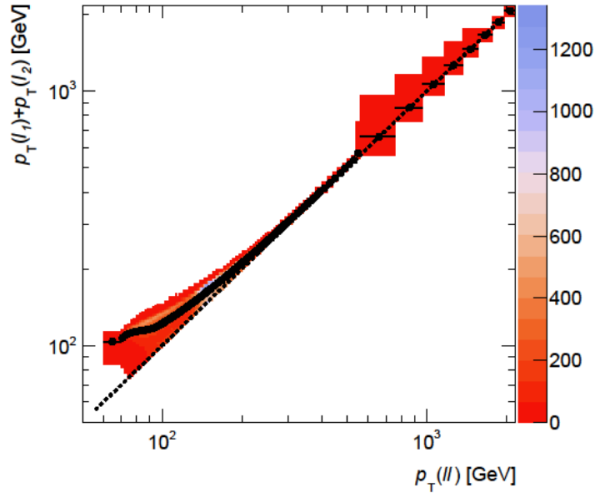


Figure 6.3: 2D distribution of $p_{T,l1} + p_{T,l2}$ versus $p_{T}^{\ell\ell}$ obtained with $Z + \text{jets}$ MC samples. The black dots correspond to the profile of this distribution, while the black dotted line corresponds to the curve $p_{T,l1} + p_{T,l2} = p_{T}^{\ell\ell}$.

6.2 First Results

6.2.1 Application to MC data

The first step of the method validation is to apply it to MC samples normalized to 1 fb^{-1} . The distributions of the variables used in the event selections after reweighting are then checked to verify the match between the reweighted $\gamma + \text{jets}$ samples and the $Z + \text{jets}$ samples in both ee and $\mu\mu$ channels. This quick check might reveal in a qualitative way if there are discrepancies between the two distributions that can lead to a bad estimation, and, in that case, where they arise from. This comparison between distributions can be seen in Figures 6.4 and 6.5 for the ee and $\mu\mu$ channels respectively.

A visual inspection of these distributions leads to the following considerations:

- $\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}})$ is well reproduced with the $\gamma + \text{jets}$ reweighting method.
- $|E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell}|/p_{\text{T}}^{\ell\ell}$ is well reproduced in the signal region (below 0.2, see Section 5.4.3).
- $E_{\text{T}}^{\text{miss}}$ shows a significant discrepancy in the signal region (above 90 GeV).
- $E_{\text{T}}^{\text{miss}}/H_{\text{T}}$ shows a significant discrepancy in the signal region (above 0.4).
- The number of b -jets is well reproduced in the signal region (no b -jets).

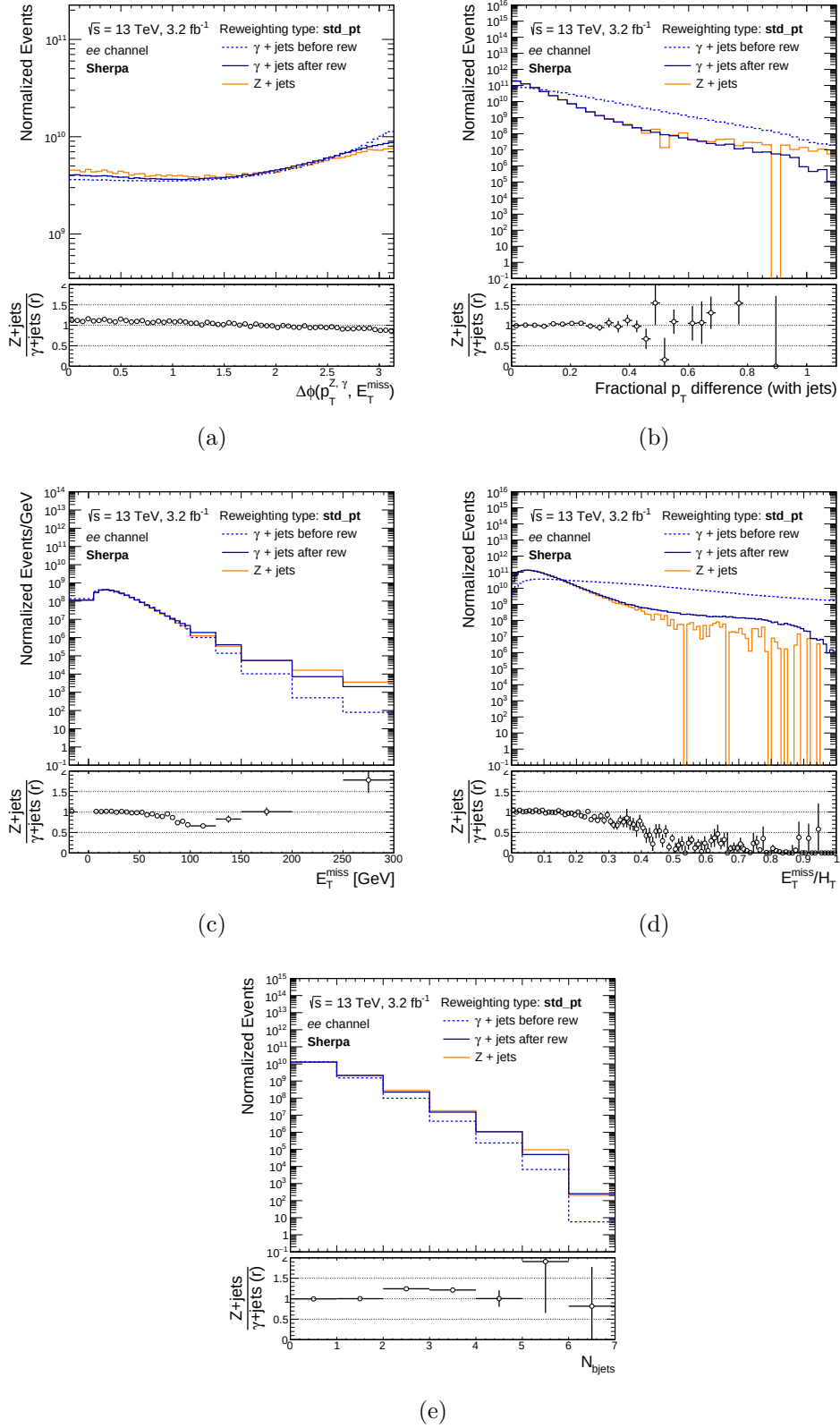


Figure 6.4: The effect of $\gamma + \text{jets}$ reweighting on the five variables used in the event selection (ee channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

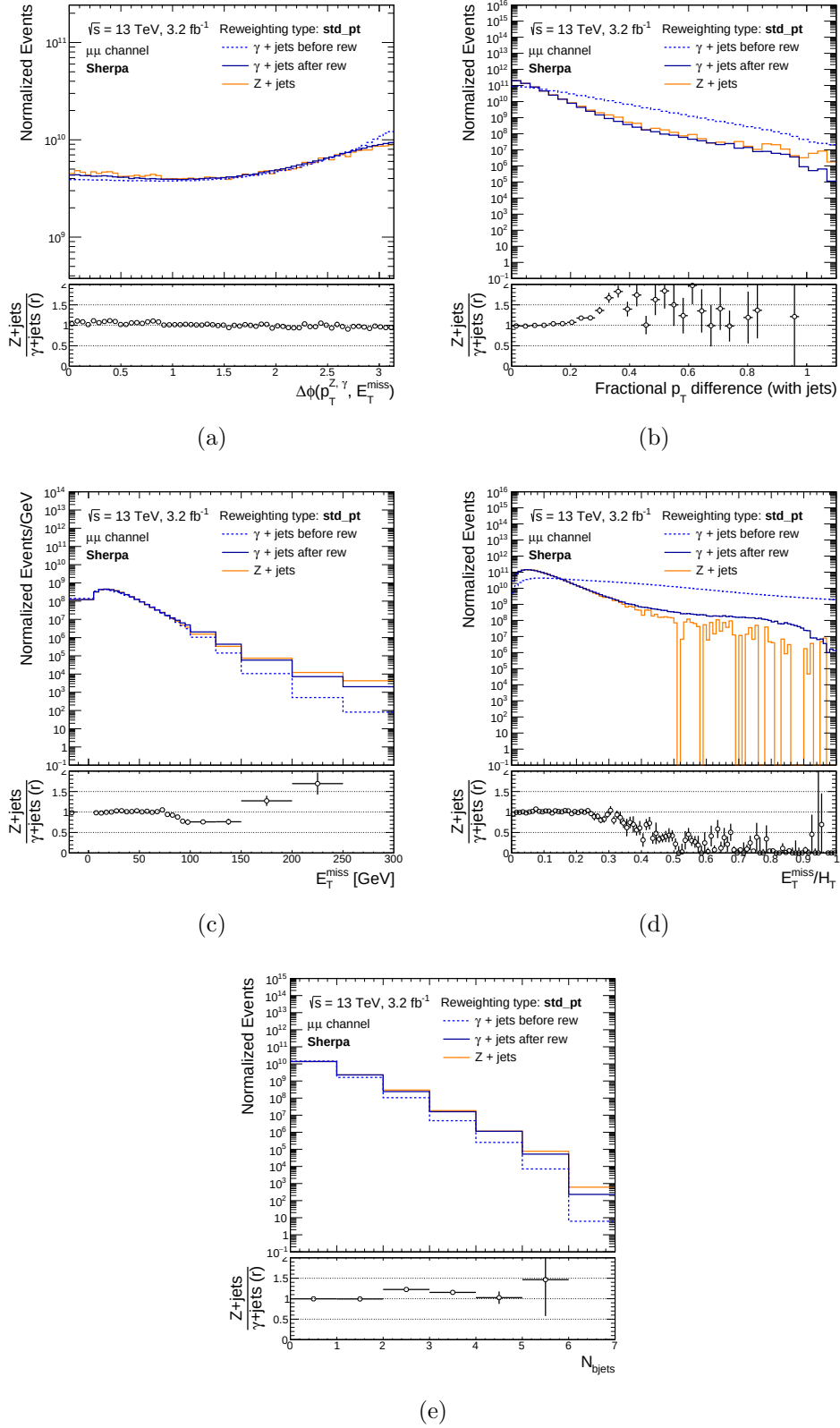


Figure 6.5: The effect of $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting ($\mu\mu$ channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss, jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

6.2.2 Event Selections after Reweighting

The effectiveness of the $\gamma + \text{jets}$ reweighting method is quantitatively verified using Monte Carlo events. In this procedure, the number of events surviving each cut are compared between $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ with the samples normalized to 1 fb^{-1} . The results of this study can be seen in Tables 6.2 and 6.3 for the ee and $\mu\mu$ channel respectively. The errors, in this case, are due to the statistics and renormalization factors of the Monte Carlo samples. The errors of the $\gamma + \text{jets}$ sample after reweighting are lower since the number of events is higher before reweighting.

Observing these results, the outlook of the event selections after reweighting shows significant discrepancies, which affect the validity of the method itself.

Cut	MC $Z + \text{jets}$ estimate	MC rew. $\gamma + \text{jets}$ estimate
Initial events	15147 ± 58	15147 ± 12
$\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}}) > 2.7$	3147 ± 28	3496 ± 6
$ E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell} /p_{\text{T}}^{\ell\ell} < 0.2$	3046 ± 27	3378 ± 6
$E_{\text{T}}^{\text{miss}} > 90 \text{ GeV}$	25.4 ± 1.5	62.0 ± 0.7
$E_{\text{T}}^{\text{miss}}/H_{\text{T}} > 0.4$	0.46 ± 0.92	19.92 ± 0.43
$b\text{-jets veto } 0.47 \pm 0.91$	19.19 ± 0.42	

Table 6.2: Comparison of event selections between $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ MC samples for the ee channel.

6.2.3 Further Investigations

To overcome the discrepancies shown in the previous section, investigations have been performed on the significant variables in the $Z + \text{jets}$ and $\gamma + \text{jets}$ events. In particular, among the plots shown in Section 6.2.1, the disagreement in the $E_{\text{T}}^{\text{miss}}$ distribution is quite relevant. Indeed, this variable does not depend on the boson's p_{T} , as it arises from jet mis-measurements.

To isolate the source of discrepancy, the $\mathbf{E}_{\text{T}}^{\text{miss}}$ vector has been divided into two components, one parallel to the boson's direction, the “Parallel” component, and one perpendicular to the boson's direction, the “Perpendicular” component. The comparison between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ distributions for these variables is shown in Figures 6.6 and 6.7 for the ee and $\mu\mu$ channel respectively. Inspecting these plots, it is evident that the source

Cut	MC $Z + \text{jets}$ estimate	MC rew. $\gamma + \text{jets}$ estimate
Initial events	16298 ± 61	16298 ± 13
$\Delta\phi(p_T^Z, E_T^{\text{miss}}) > 2.7$	3592 ± 27	3761 ± 6
$ E_T^{\text{miss, jet}} - p_T^{\ell\ell} /p_T^{\ell\ell} < 0.2$	3425 ± 26	3633 ± 6
$E_T^{\text{miss}} > 90 \text{ GeV}$	37.1 ± 2.0	66.7 ± 0.8
$E_T^{\text{miss}}/H_T > 0.4$	0.54 ± 0.87	21.89 ± 0.48
b -jets veto 0.51 ± 0.86	21.09 ± 0.47	

Table 6.3: Comparison of event selections between $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ MC samples for the $\mu\mu$ channel.

of the discrepancy lies in the Parallel component.

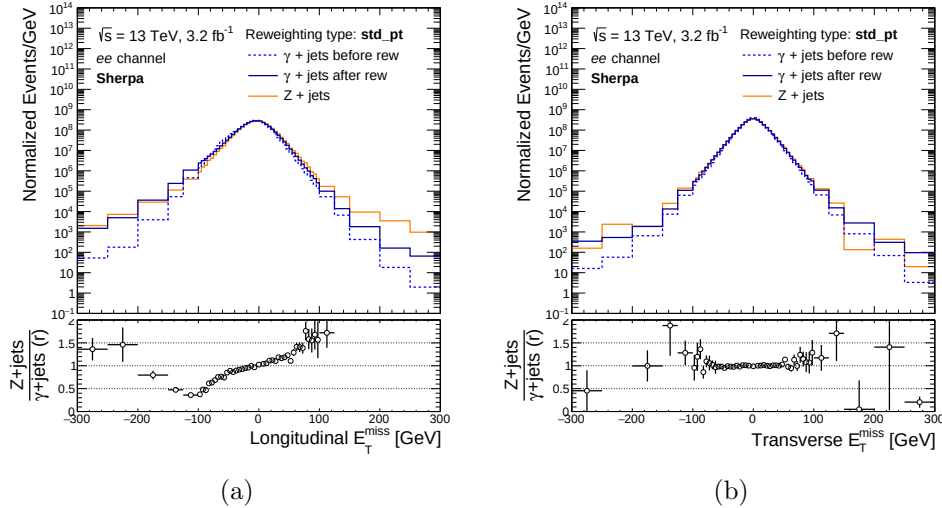


Figure 6.6: The effect of $\gamma + \text{jets}$ reweighting on the (a) Parallel and (b) Perpendicular component of E_T^{miss} , ee channel. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

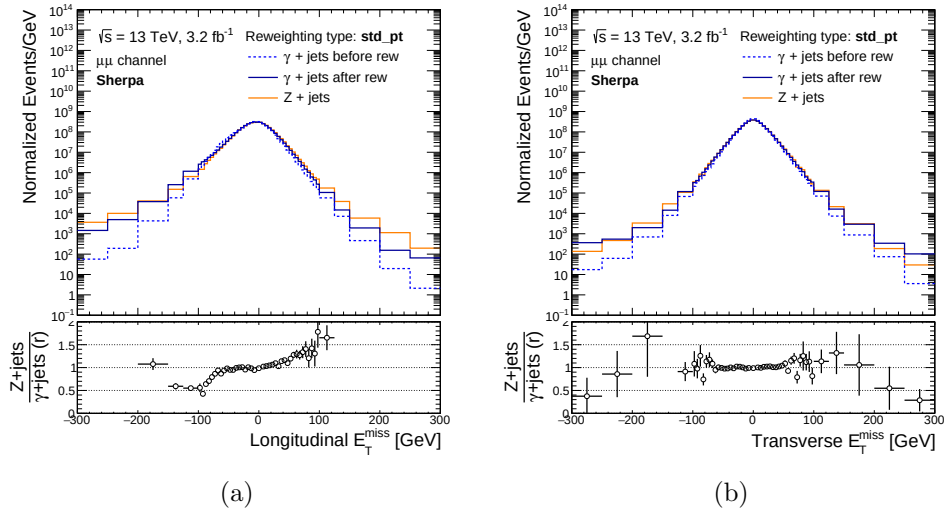


Figure 6.7: The effect of $\gamma + \text{jets}$ reweighting on the (a) Parallel and (b) Perpendicular component of $\mathbf{E}_T^{\text{miss}}$, $\mu\mu$ channel. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

Following this inspection, the Parallel component of the $\mathbf{E}_T^{\text{miss}}$ has been divided into its constituents. As shown in Equation 5.5, the $\mathbf{E}_T^{\text{miss}}$ is calculated from a “hard” and a “soft” term. The first term, in particular, is the sum of the momenta of all the objects involved in the event. In the case of $Z + \text{jets}$ and $\gamma + \text{jets}$, these are the boson (which decays into two leptons in the $Z + \text{jets}$ case) and the jets. The boson component of the E_T^{miss} is the $\mathbf{p}_T$ of the boson itself, while the jet component is the vectorial sum of all the jet momenta, i.e.

$$\mathbf{p}_T^{\text{jets}} = \sum_j^{n_{\text{jets}}} \mathbf{p}_T^j \quad (6.4)$$

where $\mathbf{p}_T^j$ is the $\mathbf{p}_T$ of the j_{th} jet ($j = 1, \dots, n_{\text{jets}}$, n_{jets} being the total number of jets). Since the boson’s p_T has been reweighted, the boson component of the $\mathbf{E}_T^{\text{miss}}$ is not in disagreement between the $Z + \text{jets}$ and the reweighted $\gamma + \text{jets}$ samples. Therefore, the distribution of the parallel component of $\mathbf{p}_T^{\text{jets}}$ has been analyzed. This is defined as

$$p_{T,P}^{\text{jets}} = \sum_j^{n_{\text{jets}}} \mathbf{p}_T^j \cdot \frac{\mathbf{p}_T^{Z/\gamma}}{p_T^{Z/\gamma}} \quad (6.5)$$

The comparison plots between $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ samples are shown in Figure 6.8 for the two analysis channels.

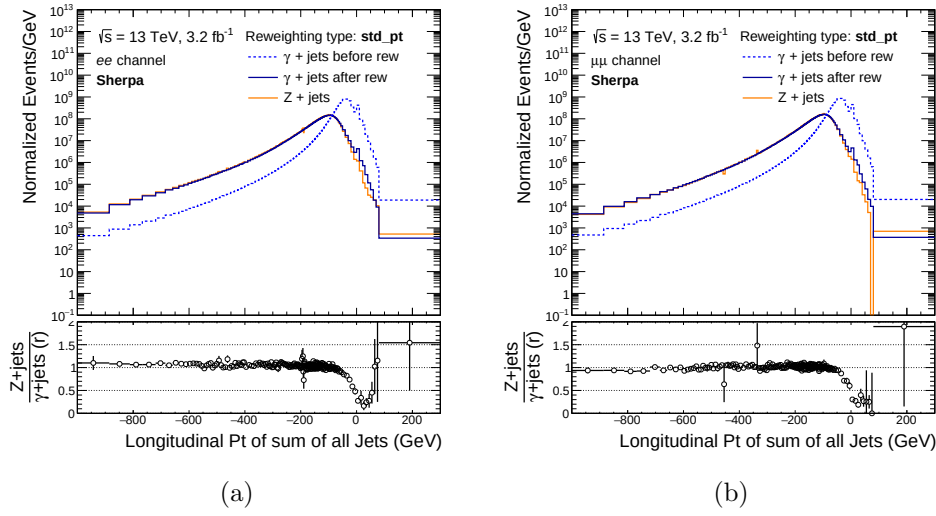


Figure 6.8: The effect of $\gamma + \text{jets}$ reweighting on $p_{T,P}^{jets}$, (a) ee channel and (b) $\mu\mu$ channel. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

These plots show clearly that there is a significant disagreement in this variable between the $Z + \text{jets}$ and the reweighted $\gamma + \text{jets}$ samples. This shows that the $\gamma + \text{jets}$ reweighting method does not properly account for the jet recoil in the event kinematic configuration. In particular, the disagreement is significant in the region of positive $p_{T,P}^{jets}$, i.e. when the jet recoil is in the same direction as the Z/γ boson. This consideration has lead to an improvement in the method itself, which will be shown in the next section.

6.3 2D $\gamma + \text{jets}$ reweighting

6.3.1 Description

As shown in the previous section, the $\gamma + \text{jets}$ reweighting method does not reproduce the $p_{T,P}^{jets}$ variable properly. To account for this discrepancy, the method has been extended to two variables, the second variable being $p_{T,P}^{jets}$ itself. According to this modification, the reweighting factor depends not only on p_T , but also on $p_{T,P}^{jets}$.

The immediate consequence of this extension is that now the $p_{T,P}^{jets}$ distribution matches by construction between $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$, as shown in Figure 6.9. Some small discrepancy can still be seen in the negative part of the distribution due to the low statistics.

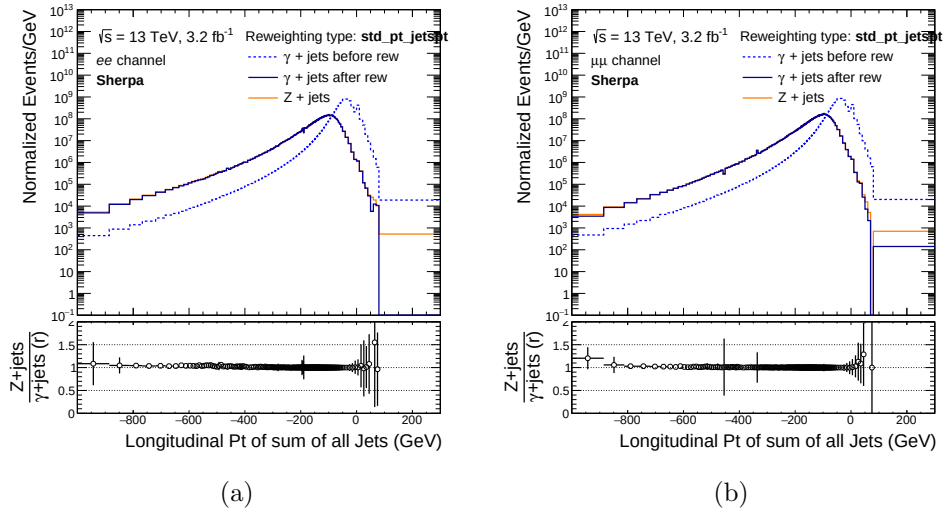


Figure 6.9: The effect of $\gamma + \text{jets}$ 2D reweighting to the $p_{T,P}^{\text{jets}}$ distribution in the (a) ee and (b) $\mu\mu$ channel. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

6.3.2 Application to MC Data

After applying the 2D-extended method, a qualitative check on the five variables used in the event selections after reweighting has been performed, as shown in Figures 6.10 (ee channel) and 6.11 ($\mu\mu$ channel).

These plots must be compared with the ones obtained with the original mono-dimensional method (Figures 6.4 and 6.5 respectively). Some preliminary observations can be drawn from this comparison:

- $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ is still well reproduced.
- $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$ is still well reproduced in the signal region (below 0.2, see Section 5.4.3).
- E_T^{miss} is now much better reproduced, even though it shows discrepancy for high values.
- E_T^{miss}/H_T still shows a significant discrepancy in the signal region (above 0.4).
- The number of b -jets is still well reproduced in the signal region (no b -jets).

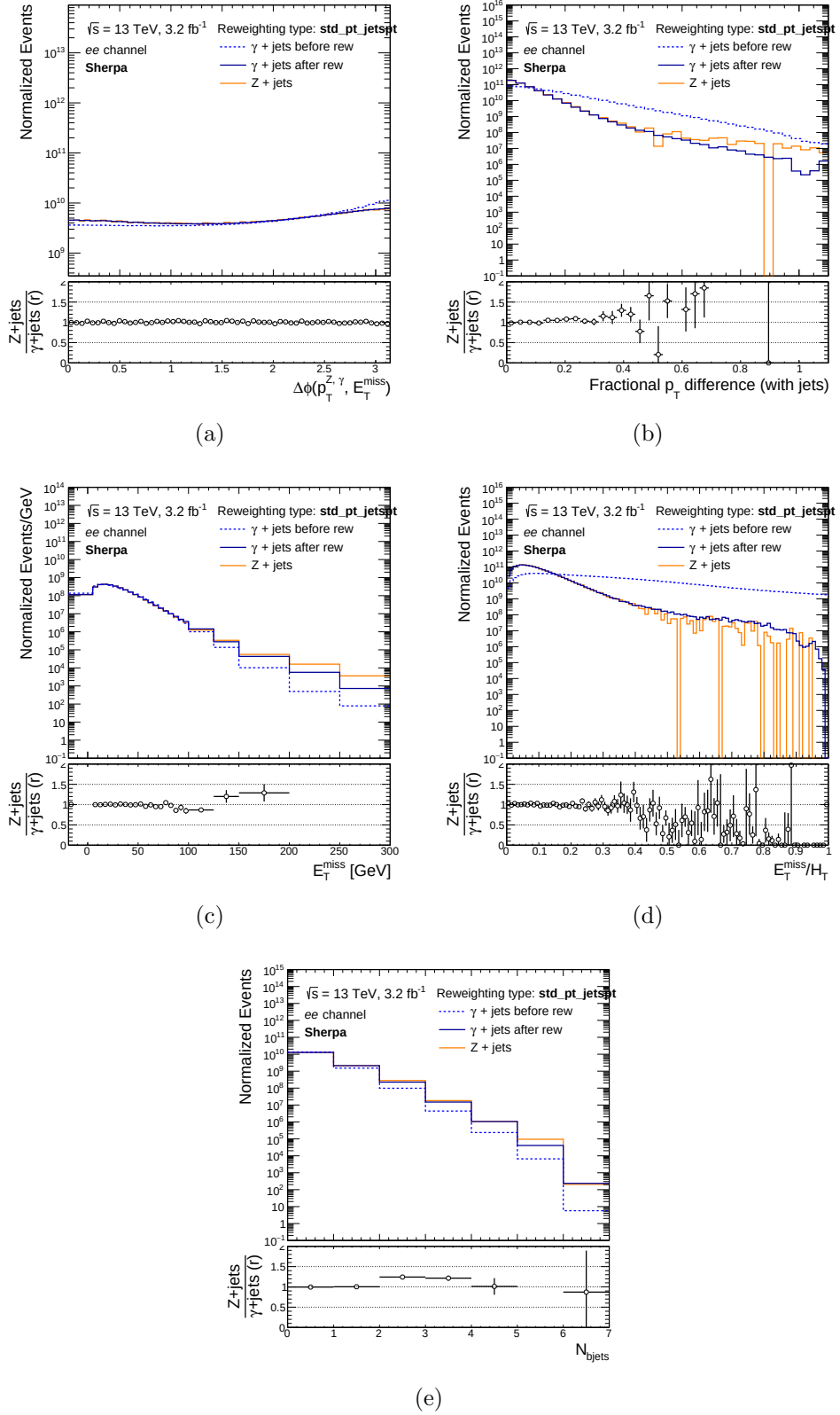


Figure 6.10: The effect of 2D $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting (ee channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

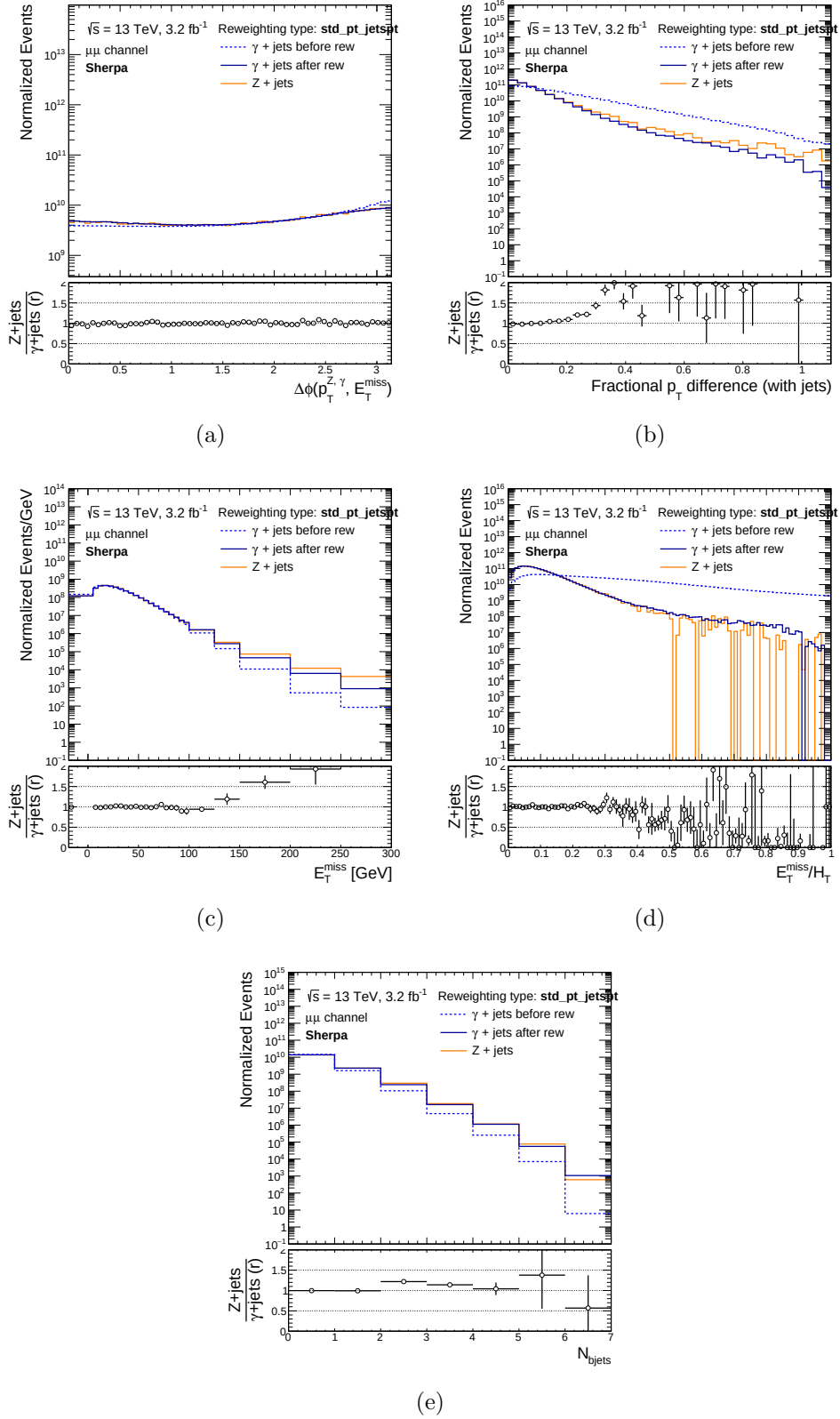


Figure 6.11: The effect of 2D $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting ($\mu\mu$ channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

6.3.3 Event Selections after Reweighting

The application of the 2D $\gamma + \text{jets}$ reweighting method on MC data (renormalized to 1 fb⁻¹) leads to the event selections after reweighting in Tables 6.4 (ee channel) and 6.5 ($\mu\mu$ channel).

Comparing these results with the original mono-dimensional $\gamma + \text{jets}$ reweighting (Tables 6.2 and 6.3 respectively), it is clear that the 2D extension of the method improves the agreement significantly, but the discrepancy is still bigger than the statistical error. Nevertheless, this partial success lead to a further modification in the reweighting procedure itself, as shown in the next section.

Cut	MC $Z + \text{jets}$ estimate	MC 2D-rew. $\gamma + \text{jets}$ estimate
Initial events	15147 $\pm$ 58	15137 $\pm$ 12
$\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}}) > 2.7$	3147 $\pm$ 28	3184 $\pm$ 5
$ E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell} /p_{\text{T}}^{\ell\ell} < 0.2$	3046 $\pm$ 27	3091 $\pm$ 5
$E_{\text{T}}^{\text{miss}} > 90 \text{ GeV}$	25.4 $\pm$ 1.5	32.0 $\pm$ 0.8
$E_{\text{T}}^{\text{miss}}/H_{\text{T}} > 0.4$	0.46 $\pm$ 0.92	6.39 $\pm$ 0.35
b -jets veto 0.47 $\pm$ 0.91	6.13 $\pm$ 0.34	

Table 6.4: Comparison of event selections between $Z + \text{jets}$ and 2D-reweighted $\gamma + \text{jets}$ MC samples for the ee channel.

Cut	MC $Z + \text{jets}$ estimate	MC 2D-rew. $\gamma + \text{jets}$ estimate
Initial events	16298 $\pm$ 61	16289 $\pm$ 13
$\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}}) > 2.7$	3592 $\pm$ 27	3565 $\pm$ 6
$ E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell} /p_{\text{T}}^{\ell\ell} < 0.2$	3425 $\pm$ 26	3458 $\pm$ 6
$E_{\text{T}}^{\text{miss}} > 90 \text{ GeV}$	37.1 $\pm$ 2.0	39.9 $\pm$ 0.8
$E_{\text{T}}^{\text{miss}}/H_{\text{T}} > 0.4$	0.54 $\pm$ 0.87	6.73 $\pm$ 0.42
b -jets veto 0.51 $\pm$ 0.86	6.62 $\pm$ 0.42	

Table 6.5: Comparison of event selections between $Z + \text{jets}$ and 2D-reweighted $\gamma + \text{jets}$ MC samples for the $\mu\mu$ channel.

6.4 Modified 2D $\gamma + \text{jets}$ reweighting

6.4.1 Description

As shown in the previous section, the 2D extension of the $\gamma + \text{jets}$ reweighting method improves the results with respect to the original method, but it does not lead to agreement between the MC samples. In extending the method there is still some level of freedom. More specifically, there are two modifications that can be done. First, one can apply some cuts from the event selections *before* the reweighting. Secondly, one can choose another variable rather than $p_{T,P}^{\text{jets}}$ as the second variable for the 2D reweighting. The choice of $p_{T,P}^{\text{jets}}$ seemed natural as it was found to be a significant source of discrepancy, but it may be more convenient to use one of the variables used in the event selections after reweighting. The method, therefore, has been modified by adding a cut and changing the second variable. More specifically, since a big discrepancy was introduced by the $E_T^{\text{miss}} > 90$ GeV selection, this cut has been applied to the $\gamma + \text{jets}$ sample before the reweighting. Furthermore, since another mis-reproduced variable is E_T^{miss}/H_T , this variable has been chosen as the second variable to use in the 2D-reweighting.

6.4.2 Application to MC Data

The effect of the modified 2D $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting is reported in Figures 6.12 and 6.13 for MC data normalized to 1 fb^{-1} in the ee and $\mu\mu$ channel respectively. From a visual inspection, these plots show that the agreement has been lost for $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ and $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$. This effect is expected because the E_T^{miss} cut has been applied to the $\gamma + \text{jets}$ samples before the reweighting. The agreement in the selection is therefore expected to be good only when the E_T^{miss} cut is applied to the $Z + \text{jets}$ events as well.

6.4.3 Event Selections after Reweighting

The results of the application of the modified 2D $\gamma + \text{jets}$ reweighting method are summarized by the event selections after reweighting in Tables 6.6 and 6.7. As outlined in the plots shown in the previous paragraph, the agreement is obtained only after the E_T^{miss} cut. Nevertheless, the final estimates show that, within the statistical errors, the agreement between the MC samples can be obtained.

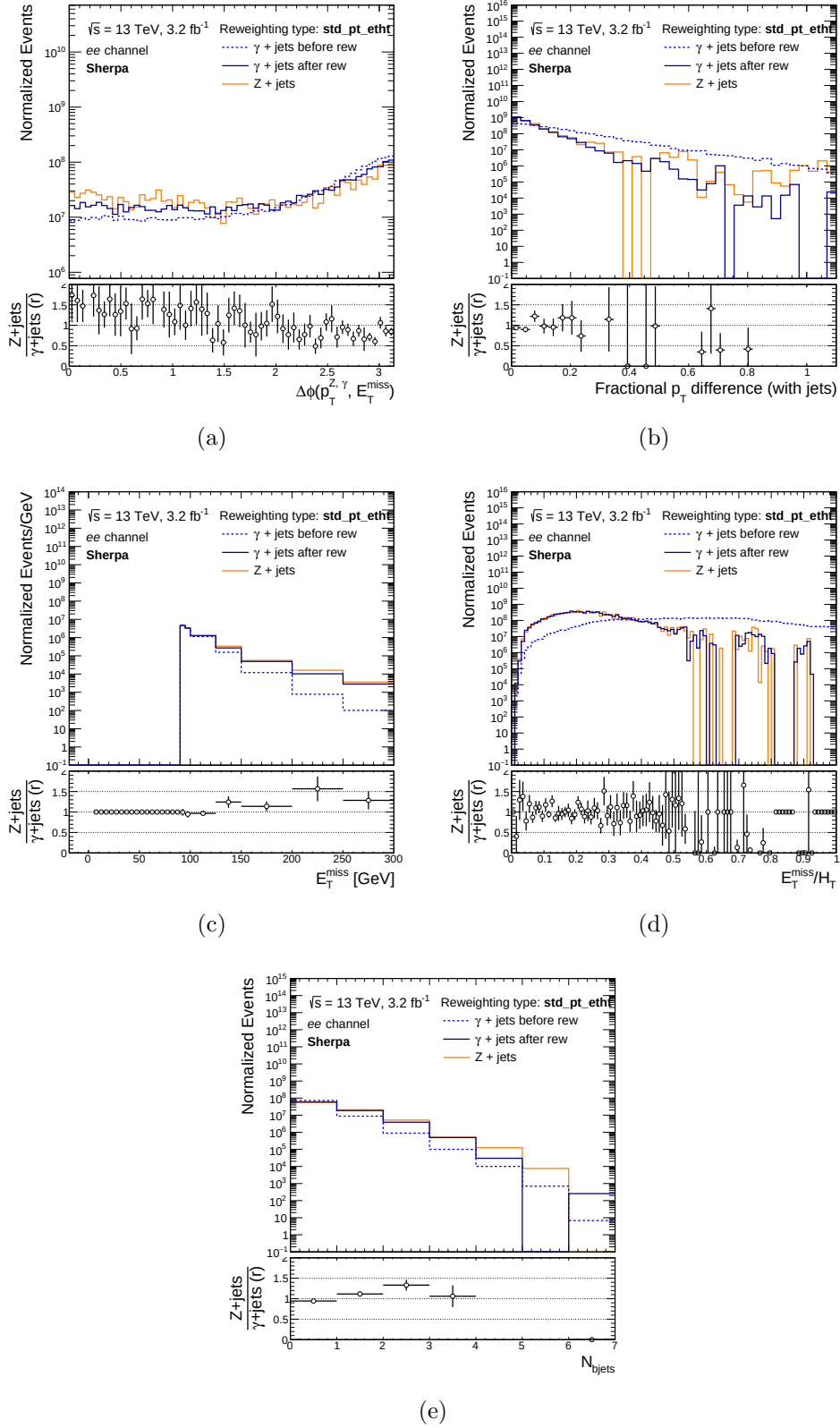


Figure 6.12: The effect of modified 2D $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting (ee channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

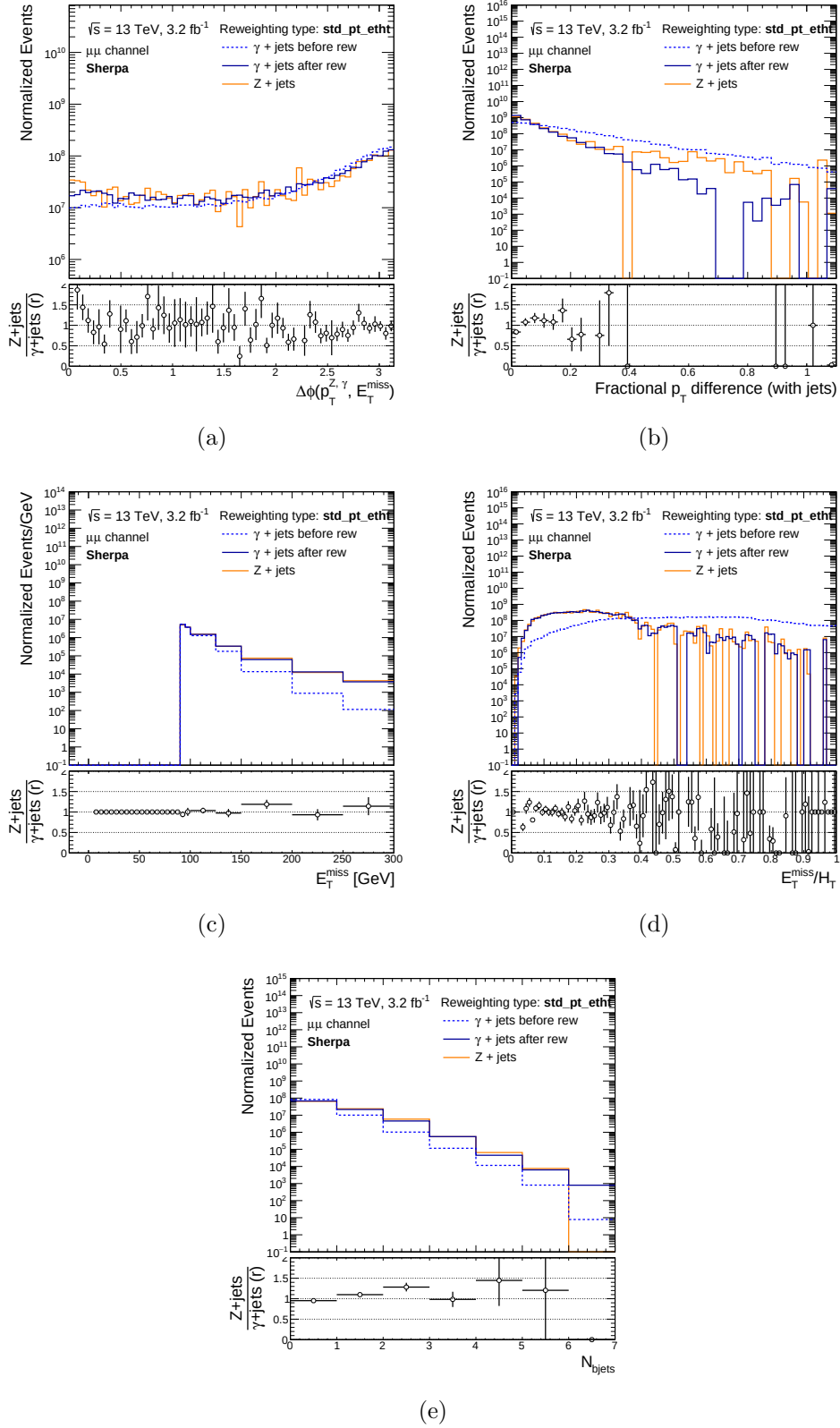


Figure 6.13: The effect of modified 2D $\gamma + \text{jets}$ reweighting on the five variables used in the event selections after reweighting ($\mu\mu$ channel): (a) $\Delta\phi(p_T^Z, E_T^{\text{miss}})$ (radians), (b) $|E_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell}$, (c) E_T^{miss} , (d) E_T^{miss}/H_T and (e) number of b -jets. Each figure features the MC p_T distributions of $Z + \text{jets}$ (red line), $\gamma + \text{jets}$ before (blue dotted line) and after (blue solid line) reweighting. The event number in each bin is normalized to the bin width. The ratio plots between the $Z + \text{jets}$ and reweighted $\gamma + \text{jets}$ p_T distributions are shown in the inserts below.

Cut	MC $Z + \text{jets}$ estimate	MC Modified 2D-rew. $\gamma + \text{jets}$ estimate
Initial events	15147 ± 58	95070 ± 1032
$\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}}) > 2.7$	3147 ± 28	20807 ± 479
$ E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell} /p_{\text{T}}^{\ell\ell} < 0.2$	3046 ± 27	20635 ± 479
$E_{\text{T}}^{\text{miss}} > 90 \text{ GeV}$	25.4 ± 1.5	30.1 ± 0.9
$E_{\text{T}}^{\text{miss}}/H_{\text{T}} > 0.4$	0.46 ± 0.92	0.61 ± 0.25
$b\text{-jets veto } 0.47 \pm 0.91$	0.60 ± 0.25	

Table 6.6: Comparison of event selections between $Z + \text{jets}$ and modified 2D-reweighted $\gamma + \text{jets}$ MC samples for the ee channel.

Cut	MC $Z + \text{jets}$ estimate	MC Modified 2D-rew. $\gamma + \text{jets}$ estimate
Initial events	16298 ± 61	20035 ± 150
$\Delta\phi(p_{\text{T}}^Z, E_{\text{T}}^{\text{miss}}) > 2.7$	3592 ± 27	5397 ± 77
$ E_{\text{T}}^{\text{miss,jet}} - p_{\text{T}}^{\ell\ell} /p_{\text{T}}^{\ell\ell} < 0.2$	3425 ± 26	5176 ± 74
$E_{\text{T}}^{\text{miss}} > 90 \text{ GeV}$	37.1 ± 2.0	38.5 ± 1.1
$E_{\text{T}}^{\text{miss}}/H_{\text{T}} > 0.4$	0.54 ± 0.87	0.70 ± 0.41
$b\text{-jets veto } 0.51 \pm 0.86$	0.61 ± 0.40	

Table 6.7: Comparison of event selections between $Z + \text{jets}$ and modified 2D-reweighted $\gamma + \text{jets}$ MC samples for the $\mu\mu$ channel.

6.5 Summary

The $Z + \text{jets}$ process constitute a non-negligible source of background for the $\ell\ell\nu\nu$ analysis. At the moment, the estimation of their yield, performed with the ABCD method, suffers from a considerable error which affects the results of the analysis, especially in the area of the searches for invisible decays of the Higgs boson. For this reason, an alternative method to improve the estimation of the $Z + \text{jets}$ yield is proposed. This method is based on applying a reweighting factor to $\gamma + \text{jets}$ events, which have a similar kinematic configuration to the $Z + \text{jets}$ events. This reweighting factor is a function of the photon's p_T and is aimed to re-shape the distributions of the kinematic variables of the $\gamma + \text{jets}$ sample to match the corresponding ones of the $Z + \text{jets}$ sample (Section 6.1.1).

To test this method, the following procedure is applied to Monte Carlo events (normalized to 1 fb^{-1}). First, some selections are applied to the $\gamma + \text{jets}$ events in order to reproduce the object selection and the event pre-selection applied to the $Z + \text{jets}$ events in the analysis (Sections 6.1.3 and 6.1.4). Afterwards, the reweighting factor is calculated and applied to the $\gamma + \text{jets}$ events. Finally, the same event selection as the analysis is applied to both $\gamma + \text{jets}$ and $Z + \text{jets}$ Monte Carlo samples (Section 6.1.5) and the number of events surviving each cut is compared between the two samples. The agreement is considered achieved when the two estimates match within the statistical errors.

The first application of this method does not lead to the expected results, as the estimate is not in agreement (Section 6.2.2). Some investigations lead to locate the problem in the jet component of the E_T^{miss} (Section 6.2.3). The proposed solution, therefore, is to extend the reweighting procedure to two variables, one being the p_T of the photon and one being the component of the jet recoil parallel to the photon. This extended method leads to an improvement in the estimate (Section 6.3.3), but the agreement is still not achieved. Two further modifications of the 2D reweighting method are then proposed. The first one is to change the second reweighting variable with one of the variables considered in the event selection. The second modification is to apply one of the selection cuts to the $\gamma + \text{jets}$ sample before reweighting. After these two modifications, the agreement between the two Monte Carlo samples is satisfactory (Section 6.4.3).

These results show that the $\gamma + \text{jets}$ reweighting method is a valid alternative for the estimation of the $Z + \text{jets}$ yield to the ABCD method. Despite some complications, the flexibility of the $\gamma + \text{jets}$ reweighting method can be exploited to apply some modifications which lead to acceptable agreement. These results are still not complete, and more work must be done to validate this method. Nevertheless, thanks to these results, the $\gamma + \text{jets}$ reweighting method is under consideration for the $\ell\ell\nu\nu$ analysis and the work shown in this chapter will be essential to its implementation.

Chapter 7

Conclusions

The ATLAS experiment at CERN has achieved impressively high performances which have led to the discovery of the Higgs boson in 2012 and many other outstanding contributions to Particle Physics.

The success of ATLAS is partly due to the excellent achievements of its tracking system, particularly the silicon pixel and strip detectors. These detectors employ the most advanced silicon technology available at the time they were built. In particular, ATLAS adopted the hybrid detector technology. In these detectors the sensitive component is connected to the read-out chip, based on CMOS technology, in a process called hybridization. The detectors produced with this technique are capable of being biased to several hundreds of Volts, and show excellent performance in terms of speed and radiation resistance.

Recent developments of the CMOS technology have allowed the insertion of the read-out circuitry directly into the sensitive component, avoiding the complications of the hybridization process. The CMOS technology has been already used in several physics experiments but the impossibility of applying a high bias voltage makes the technology unsuitable for the harsh requirements of ATLAS, since this is very important for fast signal collection and radiation hardness.

Recently new developments in the design of CMOS detectors have made it possible to apply high bias voltage thanks to protective structures surrounding the read-out electronics. These new detectors, known as DMAPS, are regarded as a valid alternative to the hybrid detectors for future particle physics experiments. The ATLAS experiment, therefore, is considering to use the DMAP detectors for the upgrade phase of the LHC, starting from 2026. In this context, several devices have been designed and produced with different implementations of the CMOS technology.

Before using these devices in ATLAS, they must be characterized with several techniques involving a variety of tools and instruments in order to verify that they meet the experimental requirements. In particular, most of the instrumentation used to obtain the results of this

thesis has been set and developed in the OPMD lab in Oxford. The techniques developed range from electrical characterization, to laser techniques, to test beams with charged particles. All these characterization methods have been crucial to achieve important results and to study the features of different devices produced with the CMOS technology.

More specifically, this thesis presents the developments of three different kinds of CMOS detectors, the LFoundry active detectors, the LFoundry passive detectors and the AMS strip CMOS detectors.

The LFoundry active CMOS detectors have been successfully characterized in many aspects. The Edge-TCT measurements performed on CCPD-LF, LF-CPIX and LF-MONOPIX prove that the depletion region extends deeply (hundreds of microns) inside the silicon bulk also after $10^{15} \text{ n}_{eq}/\text{cm}^2$ of radiation dose, as it is expected with a high resistivity substrate. Further studies with minimum ionizing particles (^{90}Sr and test beam) show that the signal is well above threshold even at such high irradiation doses. Measurements with X -ray sources confirm the good behaviour of these devices. The performance of the preamplifiers implemented in these devices, though, does not meet the LHC requirements. In the case of LF-CPIX, specifically, even though the gain is almost unchanged and the increase of noise is not significant, the preamplifiers' speed is heavily deteriorated after irradiation, as only a small portion of the signal is collected within 25 ns. The slow electronic response is problematic for the implementation of this technology for the ATLAS experiment, and improvements in the design are needed to overcome this limitation.

The LFoundry passive CMOS detectors do not implement the electronics inside the sensitive bulk, and the signal is therefore externally handled by a front-end read-out chip. This feature avoids the problem of the slow preamplifiers, but the bump-bonding process is still required for the assembly. Nevertheless, with the CMOS production process, some connections are implemented on the sensor itself, and the bump bonding process is facilitated. The studies performed with test beams on the LFoundry passive CMOS devices show a very high efficiency even after a dose of $1.14 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. In particular, the efficiency is higher if the area of the collecting diode is larger. This result is very important and must be taken into consideration in the CMOS sensor design.

The third technology considered in this thesis is the AMS strip CMOS. The HVStrip1 prototype shows a detectable signal with charged particles even after a dose of almost $10^{15} \text{ n}_{eq}/\text{cm}^2$. Unfortunately, in the case of the Chess1 prototype, no depletion region could be observed with the Edge-TCT, and many attempts of testing this device have failed.

The DMAPS technologies are very recent, and the Chess1 failure proves that their implementation can present complications and require a substantial effort to become mature enough for high energy particle physics experiments.

One of the most important achievements of the ATLAS experiment was the discovery of

the Higgs boson. Whilst many of its features have been already revealed and are consistent with the predictions of the Standard Model, the Higgs boson is expected to also be an excellent probe for new physics. In particular, the Higgs boson's coupling with invisible particles can shed light on a crucial problem of modern physics, such as the nature of Dark Matter. In this framework, the $H \rightarrow ZZ \rightarrow \ell\nu\nu$ decay channel provides a way to search for new physics. The final state of this decay can be used to search for higher mass scalar particles. The $\ell\nu\nu$ final state is also sensitive to several processes involving the Higgs boson decaying to invisible particles. Therefore, the estimation of the yield of the $\ell\nu\nu$ process must be as accurate as possible in order to be sensitive to deviations from the Standard Model predictions.

The measurement of the yield of the $\ell\nu\nu$ process is affected by a series of background processes that contaminate the signal region. The estimation of the background yields, therefore, is essential for the success of the analysis. Among all the background processes, the $Z + \text{jets}$ is one of the most problematic, and it can be evaluated using $\gamma + \text{jets}$ data. This method relies on the similarities between the $Z + \text{jets}$ and the $\gamma + \text{jets}$ processes, as they both consist of a spin-1 boson recoiling against an hadronic system. According to this method, a reweighting factor is applied to the $\gamma + \text{jets}$ events as a function of the photon's p_T , in order to reproduce the Z boson's p_T distribution of the $Z + \text{jets}$ events. This reweighting factor takes into account the differences in the cross sections, and consequently the reweighted $\gamma + \text{jets}$ events should reproduce the $Z + \text{jets}$ events with good accuracy.

The first implementation of this method does not obtain the desired results, since agreement between $Z + \text{jets}$ and $\gamma + \text{jets}$ Monte Carlo samples could not be obtained, with the reweighted $\gamma + \text{jets}$ samples having about 40 times more events than the $Z + \text{jets}$ after the selections. Further investigations of these discrepancies led to a more complex method, where the reweighting factor is calculated as a function not only of the p_T of the boson, but also of the recoiling jet system p_T . The extension to two dimensions and further modifications led to a significant improvement in the results, and the final number of events in the $Z + \text{jets}$ and $\gamma + \text{jets}$ MC samples is in agreement within statistical errors.

This study proves the feasibility of the $\gamma + \text{jets}$ reweighting method for the yield estimation of the $Z + \text{jets}$ background. The use of this method, therefore, is considered for the next developments of the $\ell\nu\nu$ analysis.

Bibliography

- [1] D. Perkins. *Introduction to high energy physics*. Addison-Weisley, 1987.
- [2] A. Martin F. Halzen. *Quarks and leptons: an introductory course in modern particle physics*. Wiley, 1984.
- [3] W. Rolnick. *The fundamental particles and their interactions*. Addison-Weisley, 1994.
- [4] Tom W. B. Kibble. The Standard Model of Particle Physics, <https://inspirehep.net/record/1334156/files/arXiv:1412.4094.pdf>. 2014.
- [5] S. F. Novaes. Standard model: An Introduction. In *Particles and fields. Proceedings, 10th Jorge Andre Swieca Summer School, Sao Paulo, Brazil, February 6-12, 1999*, pages 5–102, 1999.
- [6] David J. Gross. Asymptotic freedom and the emergence of QCD. In *The Rise of the standard model: Particle physics in the 1960s and 1970s. Proceedings, Conference, Stanford, USA, June 24-27, 1992*, pages 199–232, 1992.
- [7] Andrew Purcell. Go on a particle quest at the first CERN webfest. Le premier webfest du CERN se lance à la conquête des particules, Aug 2012. [BUL-NA-2012-269](#).
- [8] Herbert Goldstein, Charles P. Poole, and John L. Safko. *Classical Mechanics (3rd Edition)*. Addison-Wesley, 3 edition, June 2001.
- [9] Antonio Pich. The Standard Model of electroweak interactions. In *The Standard Model of electroweak interactions*, pages 1–49, 2008. [1(2007)].
- [10] Andrei D Sakharov. Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe. *Soviet Physics Uspekhi*, 34(5):392, 1991.
- [11] Monika Blanke. Introduction to Flavour Physics and CP Violation. In *Proceedings, 2016 European School of High-Energy Physics (ESHEP2016): Skeikampen, Norway, June 15-28 2016*, pages 71–100, 2017.

- [12] Andrew G. Cohen, A. De Rujula, and S. L. Glashow. A Matter - antimatter universe? *Astrophys. J.*, 495:539–549, 1998.
- [13] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13:321–323, 1964.
- [14] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13:508–509, 1964.
- [15] G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Global conservation laws and massless particles. *Phys. Rev. Lett.*, 13:585–587, 1964.
- [16] Oliver Sim Brning, Paul Collier, P Lebrun, Stephen Myers, Ranko Ostojic, John Poole, and Paul Proudlock. *LHC Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2004.
- [17] Roland Garoby. Plans for Upgrading the CERN Proton Accelerator Complex. *Journal of Physics: Conference Series*, 110, 05 2008.
- [18] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt. Parton distributions for the LHC. *Eur. Phys. J.*, C63:189–285, 2009.
- [19] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.
- [20] Joao Pequeno. Computer generated image of the whole ATLAS detector, Mar 2008.
- [21] M Aleksa, F Bergsma, P A Giudici, A Kehrli, M Losasso, X Pons, H Sandaker, P S Miyagawa, S W Snow, J C Hart, and L Chevalier. Measurement of the ATLAS solenoid magnetic field. *Journal of Instrumentation*, 3(04):P04003, 2008.
- [22] The ATLAS Collaboration. *ATLAS inner detector: Technical Design Report, 1*. Technical Design Report ATLAS. CERN, Geneva, 1997.
- [23] M Capeans, G Darbo, K Einsweiler, M Elsing, T Flick, M Garcia-Sciveres, C Gemme, H Pernegger, O Rohne, and R Vuillermet. ATLAS Insertable B-Layer Technical Design Report. Technical Report CERN-LHCC-2010-013. ATLAS-TDR-19, Sep 2010.
- [24] Karolos Potamianos. The upgraded Pixel detector and the commissioning of the Inner Detector tracking of the ATLAS experiment for Run-2 at the Large Hadron Collider. *PoS*, EPS-HEP2015:261, 2015.
- [25] E. Hines. Performance of Particle Identification with the ATLAS Transition Radiation Tracker. In *Particles and fields. Proceedings, Meeting of the Division of the American Physical Society, DPF 2011, Providence, USA, August 9-13, 2011*, 2011.

- [26] Dave Robinson. ATLAS Tracker and Pixel Operational Experience. *PoS, Vertex2016:005*, 2017.
- [27] Nikiforos Nikiforou. Performance of the ATLAS Liquid Argon Calorimeter after three years of LHC operation and plans for a future upgrade. In *Proceedings, 3rd International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA 2013): Marseille, France, June 23-27, 2013*, 2013.
- [28] Joao Pequenaio. Computer Generated image of the ATLAS calorimeter, Mar 2008.
- [29] Zhaoxia Meng. Performance of the ATLAS liquid argon calorimeter. In *Physics at the LHC2010. Proceedings, 5th Conference, PLHC2010, Hamburg, Germany, June 7-12, 2010*, pages 406–408, 2010.
- [30] L. Aperio Bella. Status of the atlas liquid argon calorimeter and its performance after two years of lhc operation. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 718:60 – 62, 2013. Proceedings of the 12th Pisa Meeting on Advanced Detectors.
- [31] Bernardo Sotto-Maior Peralva. Calibration and Performance of the ATLAS Tile Calorimeter. In *Proceedings, International School on High Energy Physics : Workshop on High Energy Physics in the near Future. (LISHEP 2013): Rio de Janeiro, Brazil, March 17-24, 2013*, 2013.
- [32] J E Mdhluli, B Mellado, and E Sideras-Haddad. Neutron irradiation and damage assessment of plastic scintillators of the tile calorimeter. *Journal of Physics: Conference Series*, 802(1):012008, 2017.
- [33] F Carrió, V Castillo, A Ferrer, L Fiorini, Y Hernandez, E Hign, B Mellado, L March, P Moreno, R Reed, C Solans, A Valero, and J A Valls. The sROD module for the ATLAS Tile Calorimeter Phase-II Upgrade Demonstrator. *Journal of Instrumentation*, 9(02):C02019, 2014.
- [34] A Artamonov et al. The ATLAS Forward Calorimeter. *Journal of Instrumentation*, 3(02):P02010, 2008.
- [35] Ana Maria Henriques Correia. The ATLAS Tile Calorimeter. Technical Report ATL-TILECAL-PROC-2015-002, CERN, Geneva, Mar 2015.
- [36] *ATLAS muon spectrometer: Technical Design Report*. Technical Design Report ATLAS. CERN, Geneva, 1997.

- [37] Joao Pequeno. Computer generated image of the ATLAS Muons subsystem, Mar 2008.
- [38] Monitored Drift Tubes Chambers for Muon Spectroscopy in ATLAS. Technical Report ATL-MUON-94-044. ATL-M-PN-44, CERN, Geneva, Jun 1994.
- [39] T. Argyropoulos et al. Cathode strip chambers in atlas : Installation, commissioning and in situ performance. In *2008 IEEE Nuclear Science Symposium Conference Record*, pages 2819–2824, Oct 2008.
- [40] Giordano Cattani and the RPC group. The Resistive Plate Chambers of the ATLAS experiment: performance studies. *Journal of Physics: Conference Series*, 280(1):012001, 2011.
- [41] Koichi Nagai. Thin gap chambers in ATLAS. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 384(1):219 – 221, 1996. BEAUTY '96.
- [42] Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System. Technical Report CERN-LHCC-2013-018. ATLAS-TDR-023, Sep 2013. Final version presented to December 2013 LHCC.
- [43] 2015 start-up trigger menu and initial performance assessment of the ATLAS trigger using Run-2 data. Technical Report ATL-DAQ-PUB-2016-001, CERN, Geneva, Mar 2016.
- [44] W Lampl, S Laplace, D Lelas, P Loch, H Ma, S Menke, S Rajagopalan, D Rousseau, S Snyder, and G Unal. Calorimeter Clustering Algorithms: Description and Performance. Technical Report ATL-LARG-PUB-2008-002. ATL-COM-LARG-2008-003, CERN, Geneva, Apr 2008.
- [45] The HL-LHC Collaboration. The HL-LHC Project. <http://hilumilhc.web.cern.ch>.
- [46] G. Apollinari et al. High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report V. 0.1. <https://doi.org/10.23731/CYRM-2017-004>, 2017.
- [47] Technical Design Report for the ATLAS Inner Tracker Pixel Detector. Technical Report CERN-LHCC-2017-021 ; ATLAS-TDR-030, CERN, Geneva, Sep 2017.
- [48] Technical Design Report for the ATLAS Inner Tracker Strip Detector. Technical Report CERN-LHCC-2017-005; ATLAS-TDR-025, CERN, Geneva, Apr 2017.
- [49] Glenn F. Knoll. *Radiation Detection and Measurement*. Wiley, 2010.

- [50] Helmut Spieler. Lectures on detector techniques, September-February 1998-1999.
- [51] Halbleiter. Semiconductor technology, from a to z. <https://www.halbleiter.org/en/>.
- [52] Wikipedia. The free encyclopedia. <https://www.wikipedia.org/>.
- [53] E. Barberis et al. Temperature effects on radiation damage to silicon detectors. *Nucl. Instrum. Meth.*, A326:373–380, 1993.
- [54] Gianluigi Casse. *Effects of hadron irradiation on the electrical properties of particle detectors fabricated with different types of silicon*. PhD thesis, Universit J. Fourier, Grenoble (FR), 1998.
- [55] Micheal Moll. *Radiation Damage in Silicon Particle Detector*. PhD thesis, Universität Hamburg, 1999.
- [56] A Chilingarov, H Feick, E Fretwurst, G Lindstrm, S Roe, and T Schulz. Radiation studies and operational projections for silicon in the ATLAS inner detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 360(1):432 – 437, 1995. Proceedings of the Sixth Pisa Meeting on Advanced Detectors.
- [57] Z. Li. Radiation damage effects in Si materials and detectors and rad-hard Si detectors for SLHC. *Journal of Instrumentation*, 4(03):P03011, 2009.
- [58] F. Lemeilleur et al. Study of characteristic of silicon detectors irradiated with 24 GeV/c protons between - 20° and +20°. *Nucl. Inst. Meth.*, A360:438–444, 1995.
- [59] The ATLAS collaboration. ATLAS pixel detector electronics and sensors. *Journal of Instrumentation*, 3(07):P07007, 2008.
- [60] The ATLAS collaboration. The silicon microstrip sensors of the ATLAS semiconductor tracker. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 578(1):98 – 118, 2007.
- [61] Veljko Radeka. Low-noise techniques in detectors. 38:217–277, 11 2003.
- [62] W. Shockley. Currents to conductors induced by a moving point charge. *Journal of Applied Physics*, 9(635), 1938.
- [63] H. W. Kraner, R. Beuttenmuller, T. Ludlam, A. L. Hanson, K. W. Jones, V. Radeka, and E. H. M. Heijne. Charge collection in silicon strip detectors. *IEEE Transactions on Nuclear Science*, 30(1):405–414, Feb 1983.

- [64] X-Ray.camera. Community for users, experts and industry of photon counting imaging devices. <http://x-ray.camera/>.
- [65] Hendrik Jansen et al. Performance of the EUDET-type beam telescopes. *EPJ Techniques and Instrumentation*, 3(1):7, Oct 2016.
- [66] L. Greiner et al. Experience from the construction and operation of the STAR PXL detector. *Journal of Instrumentation*, 10(04):C04014, 2015.
- [67] Ivan Perić. A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 582(3):876 – 885, 2007. VERTEX 2006.
- [68] Particulars. Advanced measurement systems. <http://www.particulars.si>.
- [69] Riccardo de Asmundis, Giancarlo Barbarino, Stefano Russo, Gianfranca De Rosa, Carlos Maximiliano Mollo, and Daniele Vivolo. Silicon Photo Multipliers Detectors Operating in Geiger Regime: an Unlimited Device for Future Applications. In Jeong Woo Park, editor, *Photodiodes*, chapter 9. InTech, Rijeka, 2011.
- [70] OPMD. Oxford physics microstructure detector facility. <https://www2.physics.ox.ac.uk/research/atlas/our-research-activities/advanced-sensor-development>.
- [71] A Tektronix Company KEITHLEY. 2400 series. <https://www.tek.com/keithley-source-measure-units/keithley-smu-2400-series-sourcemeter>.
- [72] A. Curioni, N. Dinar, F.P. La Torre, J. Leidner, F. Murtas, S. Puddu, and M. Silari. Measurements of ^{55}Fe activity in activated steel samples with GEMPix. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 849:60 – 71, 2017.
- [73] C. Buton, A. Dawiec, J. Graber-Bolis, K. Arnaud, J.F. Brar, N. Blanc, N. Boudet, J.C. Clmens, F. Debarbieux, P. Delpierre, B. Dinkespiller, T. Gastaldi, S. Hustache, C. Morel, P. Pangaud, H. Perez-Ponce, and E. Vigeolas. Comparison of three types of xpad3.2/cdte single chip hybrids for hard x-ray applications in material science and biomedical imaging. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 758:44 – 56, 2014.
- [74] R. Budnitz. Strontium-90 and strontium-89: A review of measurement techniques in environmental media. Retrieved from <https://escholarship.org/uc/item/3rz7s934>, 1974.

- [75] J. Bernabeu, G. Casse, C. Garcia, A. Greenall, C. Lacasta, M. Lozano, G. Pellegrini, J. Rodriguez, S. Marti-Garcia, and M. Ullan. Alibava silicon microstrip readout system for educational purposes. *Nuclear and Particle Physics Proceedings*, 273-275:2563 – 2565, 2016. 37th International Conference on High Energy Physics (ICHEP).
- [76] E Marsden and T Barratt. The probability distribution of the time intervals of a particles with application to the number of a particles emitted by uranium. *Proceedings of the Physical Society of London*, 23(1):367, 1910.
- [77] testbeam_analysis. A powerful and adaptable analysis software in Python for beam test data. https://github.com/SiLab-Bonn/testbeam_analysis.
- [78] L. Uplegger et al. The pixel tracking telescope at the Fermilab Test Beam Facility. Technical Report FERMILAB-PUB-14-212-CD, Fermilab, 2014.
- [79] M. Bubna et al. Testbeam and Laboratory Characterization of CMS 3D Pixel Sensors. *JINST*, 9:C07019, 2014.
- [80] ELSA. Electron stretcher accelerator. https://www-elsa.physik.uni-bonn.de/elsa-facility_en.html.
- [81] DESY. Test Beams at DESY. <http://particle-physics.desy.de/e252106/>.
- [82] LFoundry. A SMIC owned Company. <http://www.lfoundry.com/en/technology>.
- [83] Toko Hirono et al. Characterization of fully depleted cmos active pixel sensors on high resistivity substrates for use in a high radiation environment. In *2016 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD)*, pages 1–4, Oct 2016.
- [84] T. Wang et al. Development of a Depleted Monolithic CMOS Sensor in a 150 nm CMOS Technology for the ATLAS Inner Tracker Upgrade. *Journal of Instrumentation*, 12(01):C01039, 2017.
- [85] Toko Hirono et al. CMOS pixel sensors on high resistive substrate for high-rate, high-radiation environments. *Nucl. Instrum. Meth.*, A831:94–98, 2016.
- [86] TRIGA Reactor. Institut Josef Stefan Ljubljana. <http://www.rcp.ijs.si/ric/index-a.htm>.
- [87] Igor Mandić et al. Neutron irradiation test of depleted CMOS pixel detector prototypes. *Journal of Instrumentation*, 12(02):P02021, 2017.

- [88] The MC40 Cyclotron. Birmingham University. <http://www.np.ph.bham.ac.uk/pic/cyclotron>.
- [89] W. Snoeys, F. Faccio, M. Burns, M. Campbell, E. Cantatore, N. Carrer, L. Casagrande, A. Cavagnoli, C. Dachs, S. Di Liberto, F. Formenti, A. Giraldo, E.H.M. Heijne, P. Jarron, M. Letheren, A. Marchioro, P. Martinengo, F. Meddi, B. Mikulec, M. Morando, M. Morel, E. Noah, A. Paccagnella, I. Ropotar, S. Saladino, W. Sansen, F. Santopietro, F. Scarlassara, G.F. Segato, P.M. Signe, F. Soramel, L. Vannucci, and K. Vleugels. Layout techniques to enhance the radiation tolerance of standard CMOS technologies demonstrated on a pixel detector readout chip. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 439(2):349 – 360, 2000.
- [90] D. L. Pohl et al. Radiation hard pixel sensors using high-resistive wafers in a 150 nm CMOS processing line. *JINST*, 12(06):P06020, 2017.
- [91] Masao Okihara, Hiroki Kasai, Noriyuki Miura, Naoya Kuriyama, and Yoshiki Nagatomo. Lapis SOI Pixel Process. In *Proceedings, International Workshop on SOI Pixel Detector (SOIPIX2015): Sendai, Miyagi, Japan, June 03-06, 2015*, 2015.
- [92] B.T. Huffman et al. Radiation hardness of two CMOS prototypes for the ATLAS HL-LHC upgrade project. *Journal of Instrumentation*, 11(02):C02005, 2016.
- [93] Abdelhak Djouadi. The anatomy of electro-weak symmetry breaking. I: the Higgs boson in the Standard Model. *Phys. Rept.*, 457:1–216, 2008.
- [94] P.W. Higgs. Broken symmetries, massless particles and gauge fields. *Physics Letters*, 12(2):132 – 133, 1964.
- [95] Sheldon L. Glashow. Partial-symmetries of weak interactions. *Nuclear Physics*, 22(4):579 – 588, 1961.
- [96] Steven Weinberg. A model of leptons. *Phys. Rev. Lett.*, 19:1264–1266, Nov 1967.
- [97] ATLAS collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 716(1):1 – 29, 2012.
- [98] The CMS collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716(1):30 – 61, 2012.
- [99] S. Dittmaier et al. Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables. Technical Report CERN-2011-002, 2011.

- [100] D. et al. de Florian. Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector. Technical Report FERMILAB-FN-1025-T, Oct 2016.
- [101] C. Patrignani et al. Review of Particle Physics. *Chin. Phys.*, C40(10):100001, 2016.
- [102] Giacomo Artoni et al. Study of $\ell^+\ell^-+E_{\text{T}}^{\text{miss}}$ with proton-proton collisions at $\sqrt{s}=13$ TeV in the HZZ group: introduction of common analysis strategies. Technical Report ATL-COM-PHYS-2016-1602, CERN, Geneva, Nov 2016.
- [103] Giacomo Artoni, David Axen, Artem Basalaev, Eleonora Benhar Noccioli, Daniela Bortoletto, Roberto Di Nardo, Alison Elliot, Oleg Fedin, Cong Geng, Wen Guo, Kenji Hamano, Sarah Heim, Kota Kasahara, Richard Keeler, Michel Lefebvre, Bo Liu, Victor Maleev, Rachid Mazini, Kayla McLean, Robert McPherson, Jochen Meyer, Eleni Mountricha, Iouri Naryshkin, Hideki Okawa, Mariyan Petrov, Gabriele Sabato, Arthur Schaffer, Ian Peter Joseph Shipsey, Monica Trovatelli, Fumihiko Ukegawa, Luigi Vignani, Yusheng Wu, and Bing Zhou. Search for invisible decays of the Higgs boson and for Dark Matter produced in association with a Z boson at $\sqrt{s}=13$ TeV with the ATLAS detector. Technical Report ATL-COM-PHYS-2016-1610, CERN, Geneva, Nov 2016.
- [104] K. Griest and H.E. Haber. Invisible decays of Higgs bosons in supersymmetric models. *Phys. Rev. D; (United States)*, 3(37), 2 1988.
- [105] G Blanger, F Boudjema, A Cottrant, R.M Godbole, and A Semenov. The MSSM invisible Higgs in the light of dark matter and g_2 . *Physics Letters B*, 519(1):93 – 102, 2001.
- [106] Gian F. Giudice, Riccardo Rattazzi, and James D. Wells. Gravitational scalars from higher-dimensional metrics and curvature-Higgs mixing. *Nuclear Physics B*, 595(1):250 – 276, 2001.
- [107] J. F. Gunion M. Battaglia, D. Dominici and J. D. Wells. The Invisible Higgs decay width in the add model at the LHC. 2004.
- [108] Robert E. Shrock and Mahiko Suzuki. Invisible Decays of Higgs Bosons. *Phys. Lett.*, 110B:250, 1982.
- [109] Anjan S. Joshipura and Saurabh D. Rindani. Majoron models and the Higgs search. *Phys. Rev. Lett.*, 69:3269–3273, 1992.
- [110] M. C. Bento, O. Bertolami, R. Rosenfeld, and L. Teodoro. Self interacting dark matter and invisibly decaying Higgs. *Phys. Rev.*, D62:041302, 2000.

- [111] Christoph Englert, Tilman Plehn, Dirk Zerwas, and Peter M. Zerwas. Exploring the Higgs portal. *Physics Letters B*, 703(3):298 – 305, 2011.
- [112] Benjamin W. Lee and Steven Weinberg. Cosmological lower bound on heavy-neutrino masses. *Phys. Rev. Lett.*, 39:165–168, Jul 1977.
- [113] M. Aaboud et al. Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Lett.*, B776:318–337, 2018.
- [114] Giacomo Artoni, David Axen, Artem Basalaev, Eleonora Benhar Noccioli, Daniela Bortoletto, Denys Denysiuk, Roberto Di Nardo, Alison Elliot, Oleg Fedin, Cong Geng, Wen Guo, Kenji Hamano, Sarah Heim, Xiangyang Ju, Kota Kasahara, Richard Keeler, Michel Lefebvre, Bo Liu, Victor Maleev, Rachid Mazini, Kayla McLean, Robert McPherson, Jochen Meyer, Eleni Mountricha, Iouri Naryshkin, Hideki Okawa, Mariyan Petrov, Pavel Podberezko, Gabriele Sabato, Arthur Schaffer, Ian Peter Joseph Shipsey, Birgit Sylvia Stapf, Monica Trovatelli, Fumihiko Ukegawa, Luigi Vigani, Yusheng Wu, and Bing Zhou. Search for heavy resonances in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ final state with proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. Technical Report ATL-COM-PHYS-2016-1601, CERN, Geneva, Nov 2016.
- [115] Nikolas Kauer and Giampiero Passarino. Inadequacy of zero-width approximation for a light Higgs boson signal. *JHEP*, 08:116, 2012.
- [116] The ATLAS Collaboration. Electron efficiency measurements with the ATLAS detector using the 2015 LHC proton-proton collision data. Technical Report ATLAS-CONF-2016-024, CERN, Geneva, Jun 2016.
- [117] The ATLAS Collaboration. Electron efficiency measurements with the ATLAS detector using 2012 LHC proton–proton collision data. *The European Physical Journal C*, 77(3):195, Mar 2017.
- [118] Georges Aad et al. Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV. *Eur. Phys. J.*, C76(5):292, 2016.
- [119] Georges Aad et al. Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1. *Eur. Phys. J.*, C77:490, 2017.
- [120] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. The anti- k_t jet clustering algorithm. *JHEP*, 04:063, 2008.

- [121] M. Aaboud et al. Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Rev.*, D96(7):072002, 2017.
- [122] Georges Aad et al. Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010 with the ATLAS detector. *Eur. Phys. J.*, C73(3):2306, 2013.
- [123] The ATLAS Collaboration. Selection of jets produced in 13 TeV proton-proton collisions with the ATLAS detector. Technical Report ATLAS-CONF-2015-029, CERN, Geneva, Jul 2015.
- [124] Georges Aad et al. Characterisation and mitigation of beam-induced backgrounds observed in the ATLAS detector during the 2011 proton-proton run. *JINST*, 8:P07004, 2013.
- [125] Georges Aad et al. Performance of b -Jet identification in the ATLAS Experiment. *JINST*, 11(04):P04008, 2016.
- [126] ATLAS JetEtMiss Performance Group. Usage of missing ET in analyses: rebuilding and systematics. <https://twiki.cern.ch/twiki/bin/view/AtlasProtected/METUtilities>.
- [127] ATLAS JetEtMiss Performance Group. Missing Transverse Momentum Reconstruction in Run II. <https://twiki.cern.ch/twiki/bin/view/AtlasProtected/MissingETReconstruction>.
- [128] The ATLAS Collaboration. Selection of jets produced in 13 TeV proton-proton collisions with the ATLAS detector. Technical Report ATLAS-COM-CONF-2015-024, CERN, Geneva, May 2015.
- [129] Carlo Oleari. The POWHEG-BOX. *Nucl. Phys. Proc. Suppl.*, 205-206:36–41, 2010.
- [130] Nikolas Kauer. Interference effects for $H \rightarrow WW/ZZ \rightarrow \ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ searches in gluon fusion at the LHC. *JHEP*, 12:082, 2013.
- [131] T. Gleisberg et al. Event generation with SHERPA 1.1. *JHEP*, 02:007, 2009.
- [132] S. Ask, M. A. Parker, T. Sandova, M. E. Shea, and W. J. Stirling. Using $\gamma +$ jets production to calibrate the Standard Model $Z(\rightarrow \nu\bar{\nu}) +$ jets background to new physics processes at the LHC. *Journal of High Energy Physics*, 2011(10):58, Oct 2011.
- [133] The ATLAS collaboration. Photon identification in 2015 ATLAS data. 2016.
- [134] Morad Aaboud et al. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data. *Eur. Phys. J.*, C76(12):666, 2016.

- [135] The ATLAS Collaboration. Another Search for strongly produced supersymmetric particles in final states containing a same-flavour opposite-sign dilepton pair, jets and missing transverse momentum in 13 TeV pp collisions. Technical Report SUSY-2016-13, CERN, Geneva.
- [136] The ATLAS Collaboration. Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Rev. D*, 83:052005, Mar 2011.
- [137] ATLAS Analysis Harmonization Group. Official isolation working points. <https://twiki.cern.ch/twiki/bin/view/AtlasProtected/IsolationSelectionTool>.