

**Neutron radiation damage of plastic
scintillator UPS 923A and a data driven
method in the $Zh + E_{miss}^T$ search at the
LHC**



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WITWATERSRAND,
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by

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A dissertation submitted to the University of the Witwatersrand for the degree of:

Master of Science in Physics

Supervised by

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2018

Declaration

I, Skhathisomusa Dumani Mthembu, hereby declare that the work contained in this dissertation is my original work, and that any work done by others or by myself previously has been acknowledged and referenced according to the requirements of the Faculty of Science of the University of the Witwatersrand.

This dissertation has produced three conference proceedings as listed below:

- Data driven method for predicting the shape of the dijet mass in $Zh + E_{miss}^T$ analysis. *Conference of the South African Institute of Physics (SAIP2016)*, University of Cape Town, South Africa, July, 2016. arXiv:1703.00215; **Contribution:** Background suppression cut flow, observable distributions for 1 and 2 b-tags and ratio plots for the background predictions.
- The production of the heavy scalar H in association with top and anti-top quarks. *Conference for High Energy Physics (HEPP2016)*, University of the Witwatersrand, South Africa, February, 2016 arXiv:1702.08772; **Contribution:** Cross section calculations during the production of H and observable distributions in H production.
- The influence of neutron radiation damage on the optical properties of plastic scintillator UPS 923A. *Conference for High Energy Physics (HEPP2017)*, University of the Witwatersrand, South Africa, February, 2017, *J. Phys.: Conference Series* **889** (2017), no. 10 100001; **Contribution:** Radiation damage testing results and plots for transmittance, luminescence and light yield studies.

A handwritten signature in black ink, featuring a large, stylized initial 'S' followed by a series of loops and a long horizontal stroke.

Skhathisomusa Dumani Mthembu

October 31, 2018

Abstract

Plastic scintillators, exposed to radiative environments from high energy charged particles traversing through them in the LHC at CERN, undergo radiation damage. This damage is characterized in terms of the transmittance, luminescence and light yield optical properties of the plastic are tested for changes resulting from exposure of these plastic scintillator samples to fast neutrons of varying fluences. The neutron irradiation was carried out at the IBR-2 reactor of the Frank Laboratory for Nuclear Problems at the Joint Institute for Nuclear Research, at fluences of $1.8 \cdot 10^{14}$, $1.7 \cdot 10^{13}$ and $3.8 \cdot 10^{12}$ neutrons/cm², and compared to a control sample. Results show a small change in the transmittance of the higher energy visible spectrum, and a noticeable change in the light yield of the samples as a result of the damage. There is no change observed on the luminescence as a result of radiation damage at studied fluences, and higher energy fast neutron irradiation is needed for more conclusive results.

Another contribution to this research is a data-driven method employing an effective field theory approach, with the addition of two real scalars, H and χ , introduced and added to SM particles to study the associated Higgs boson production with top quarks at the Large Hadron Collider, at a centre of mass energy of $\sqrt{s} = 8$ TeV. A benchmark scenario, where the parameters of the model are constrained for $m_H = 275$ GeV and $m_\chi = 60$ GeV, is considered. From this, a comparative study was performed for the production of the Higgs boson, in association with a single top and top-pairs in the standard model, regarding the processes with h being replaced by the heavy scalar H , further decaying through the channel $H \rightarrow h\chi\chi$. This study is performed for a single lepton channel first, and then for same-sign leptons, electrons or muons in dilepton events. Different observables, such as b - and c -tagged jet multiplicities, total missing energy, and total scalar sum of transverse momenta of all jets and leptons, are presented.

Considering the introduced scalars H and χ , an analysis for new physics searches

in the Zh channel with missing energy final states at the LHC. The analysis involves the consideration of a CP -odd, gluon-fusion-produced scalar A decaying into a heavy CP -even neutral scalar H with Z boson as $A \rightarrow ZH$. H further decays into the CP -even SM Higgs boson h in association with dark matter candidate χ - a source of missing energy. The signal final state products are described by $Z \rightarrow l^+l^-$ (where $l^\pm = e^\pm, \mu^\pm$) and $h \rightarrow b\bar{b}$ decay modes is presented. The masses of the particles presented are considered as $m_h = 125$ GeV, $m_\chi = 60$ GeV, $2m_h < m_H$ and $m_A > m_H$. Background, from quantum chromodynamic events, is suppressed by imposing selections on the observables. The decreased event numbers for single top, diboson, top pair, W + jets and Z + jets are then compared for same-flavour and for different-flavour decay schemes. This comparison is plotted as a ratio between the two decay schemes.

Acknowledgements

I would like to express my deep gratitude to my supervisor, Prof. Bruce Mellado, for introducing me to High Energy Physics analysis and experimentation, and granting me opportunities to explore these globally. Thank you for seldom intervening, and allowing me the freedom to explore my own ideas and learn in my own alternative way. I am grateful for the Joint Institute for Nuclear Research, in particular: Dr. Yuri Davydov for his supervision on radiation damage testing over my first time doing research abroad, Vladimir Baranov for his expert knowledge of electronics and willingness to share it, S. Kulikov and his colleagues for the irradiation of the samples for radiation damage experiments, and the rest of the office for the 11am tea that made my stay in a small Russian town more homely. I would like to thank Dr. Rudolph Erasmus for allowing me to use the spectrophotometer for cross-checking my work and the laser for the luminescence studies. I would like to thank the High Energy Physics Group at the University of the Witwatersrand for fruitful discussions on the scope and direction of this research.

Additionally, I would like to express thanks to the following people:

- Prof. Elias Sideras-Haddad for his mentoresque advice and assistance in thinking about my research.
- The office of P242, et al., particularly: Robert, Shell-May, Tshidiso, Stefan, Abdulazem, Dingane and Harshna.
- Mukesh for tirelessly helping me improve how I think about science, how I write, and having high expectations.
- My friends. Titus Masike, Dr. Vuyane Mhlomi, Tshidiso Ramogale, Ayanda Bam, Dennis Zheng, Fuaad Abdool, Linina Jurbandam-Bedhesi and others.
- Christopher Daryl Joseph Scott.

- My family of aunts in their varying degrees of help and support.

I would like to express my gratitude to the National Research Foundation (NRF) and iThemba LABS for financial support. The opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF or iThemba LABS.

For my late grandmother, Linah Mthembu, whose unreasonable wish for my education is no longer unreasonable nor is it any longer a wish.

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Chapter 1

Introduction

Scintillators are materials that exhibit luminescence under the presence of ionising radiation. As a result of this luminescence, radiation measurements could be performed, historically, by observing the brightness and intensity of the flashes produced by the radiation incident on the scintillator. There are two common types of scintillators, namely organic and inorganic, with primary differences being structural and from their interactions with ionising radiation. Inorganic scintillators are crystals made from oxides such as bismuth germanate, or alkali halides such as sodium iodide and cesium iodine. Organic scintillators, under which plastic scintillators fall, are of particular interest because of their use in high energy physics for the indirect measurement of the momentum and charge of particles incident on and traversing through them. This makes them crucial in many scientific and industrial fields where the identification and detection of energetic particles is vital [1]

A direct result of detection, on a larger scale, is the ability to generate and test scientific models that explain particle interactions - among other things. The Higgs boson discovery in 2012 was made possible by the detection of its decay particles. The tile calorimeter, known as the TileCal as discussed in section 2.2.2, is, in part, made up of plastic scintillators. The properties of the plastic scintillator are, therefore, vital in understanding the Higgs boson. After the discovery of the Higgs boson from ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) experiments, as discussed in section 2.2, a multitude of excesses associated with the Higgs boson have been observed and modelled by many scientists. One of these models, work actively led by the University of the Witwatersrand¹, attempts to explain these excesses by introducing a charge-parity even scalar H , together

¹For more information, please refer to the Wits HEP site here or go to url: <http://hep.wits.ac.za/publications/publications.php>.

with a single neutral scalar dark matter candidate (χ) considered to be stable and a possible source of missing transverse energy E_{miss}^T , in an effective theory. Extending to this “ground up” approach, a two Higgs doublet model (2HDM) was introduced. This encompasses the dark matter candidate χ and a Higgs-like scalar S [2]. The basis of the analytical part of this dissertation is fashioned on the preliminary model introducing the heavy scalar H as:

$$pp \rightarrow A \rightarrow ZH \quad (1.1)$$

$$Z \rightarrow l^+ l^- \quad (1.2)$$

$$H \rightarrow h \chi \chi \quad (1.3)$$

$$h \rightarrow b \bar{b} \quad (1.4)$$

where pp represents proton collisions as they occur in the LHC, A is the introduced charge-parity odd scalar which decays to the Z boson and the heavy scalar H . This heavy scalar decays into the standard model (SM) Higgs boson h and two dark matter candidates χ .

1.1 Dissertation overview

This dissertation is contained in six chapters, with two main research foci. Chapter one introduces the experiments at a grass-roots level, together with the fundamental aims and objectives of and behind the questions explored in the rest of the dissertation. The second chapter discusses the relation of the conducted experiments to the ATLAS detector, the radiation environment of the detector and why radiation damage is studied. A skeletal rationale supporting the ZH search with missing transverse momentum is introduced in this chapter. The third chapter is self contained, and covers all the plastic scintillator and radiation damage details from the experimental setup to the results and discussion. The fourth chapter discusses the production of the heavy scalar H from an effective theory, involving the production and decay of H into the standard model Higgs boson h and it’s final state products. This chapter also serves as a building block for the analysis presented in chapter five. Chapter five presents the formalism and results of the dijet mass predictions in the ZH analysis with missing transverse energy ($Zh + E_{miss}^T$). The last chapter concludes the dissertation.

1.2 Motivation

The LHC is the largest and most powerful particle accelerator built to date, operating at a center of mass energy, $\sqrt{s}$, of 7 TeV during the Run I data taking period, between 2009 and 2012, generating proton-proton (pp) collisions. ATLAS is one of the two large general purpose detectors, the other being the CMS, centred at one of the eight collision points of the LHC.

In July 2012, the ATLAS and CMS community announced the discovery of a particle with approximately 126 GeV of mass, the standard model (SM) Higgs boson [3, 4] in pp collisions using datasets corresponding to 4.8 fb^{-1} and 5.1 fb^{-1} . This particle, the quantised excitation of the Higgs field, is important in SM understanding because its discovery and the understanding of the field explains why some particles are massive (as in have mass) in a vacuum when the symmetries governing their interaction suggests they be massless.

After this discovery, an excess in the production cross section of the Higgs boson, it's production, and it's decay arose from both ATLAS and CMS observations [5]. These excesses were not consistent with SM predictions. In an attempt to explain these excesses, the University of the Witwatersrand hypothesized the existence of a heavy scalar boson H in the production mechanism of the Higgs boson, discussed further in section 5.1. This particle is coupled to an intermediate scalar, S , which couples to a dark matter (DM) candidate, χ [6], with the DM candidate (χ) being a possible source for the E_{miss}^T for the explanation of the observed excesses [7].

With the use of the above model, the Higgs boson would “recoil” against the χ and gain transverse momentum p_T . A study was conducted for the search of events with missing energy final states at the LHC considering the leptonic decay of Z by $Z \rightarrow l^+l^-$ and the standard model Higgs boson decaying to bottom quarks by $h \rightarrow b\bar{b}$ [8]. The findings thereof shall be discussed in the subsequent chapters.

1.3 Research aims and objectives

The key aim of the radiation damage experiment is to comprehensively study the effects of neutron-induced radiation damage on plastic scintillator UPS 923A used in the muon detector of the Collider Detector at Fermilab (CDF), the world's former highest-energy particle detector. This requires the investigation and understanding of neutron-matter interactions and how fast neutrons affect the nuclear structure of

the scintillator and its constituents. Changes in the scintillator properties, particularly those properties studied in the detection of decay particles (see section 3.2), influence the validity of particle detection. This investigation will aid in understanding how this ‘damage’ influences the scintillating qualities (optical properties) of the plastic in question. The understanding of this damage shall, as a consequence of the detector applications of plastic scintillators, quell detector uncertainty in Higgs boson searches.

The primary aim of the analysis study is to compare same-flavour and different-flavour lepton final states from the decay of the Z boson analytically. In so doing, the validity of a data-driven method, used to infer the dijet mass of the Z boson decay using the ratio of same-flavour and different-flavour decay schemes, shall be investigated.

To achieve these aims, the following objectives have been set:

1. Observe the optical properties of plastic scintillators exposed to varying radiation fluences.
 - Relate the radiation dosage with the change in optical properties
 - Attribute these changes to the nuclear structure of the plastic scintillator affected
2. Generate data samples and use those for analysis
 - Generate data samples from available ATLAS datasets
 - Decay, shower and hadronise generated data to simulate the conditions of the LHC and surrounding detectors
 - Remove unrelated background products and investigate only those from the desired signal
 - Discuss the results and how these can be used to determine the shape of the dijet mass m_{ll} spectrum

Chapter 2

CERN, LHC and ATLAS

2.1 CERN and the Large Hadron Collider

The European Laboratory for Particle Physics (CERN), located on the French and Swiss border outside Geneva, is a nuclear research institution known for its synergistic collaborative work. This multidisciplinary institution involves scientists and engineers all over the world with the intention of probing the fundamental structure of the universe. CERN operates the Large Hadron Collider (LHC), seen in figure 2.1, currently the world's largest and most powerful elementary particle accelerator, a proton-proton collider with 14 TeV center of mass energy. Of the large experiments constructed around the LHC ring, two of pressing importance in the study of plastic scintillators and particle interaction analysis are ATLAS (A Toroidal LHC Apparatus) [9] and the CMS (Compact Muon Solenoid) [10] which are optimized to study new physics at the TeV scale. In 2012, after three years of operation, both ATLAS and CMS announced the discovery of a new particle having a mass of approximately 125 GeV. This discovery was consistent with the standard model (SM) Higgs boson.

The LHC operational stages are defined by three main categories: Phase, Long Shutdown and Run. Phase-I and Phase-II refer to the LHC machine and detector upgrades anticipated to be completed in 2018 and 2022 respectively. The terms LS1, LS2 and LS3 refer to the long shutdowns of the LHC in 2013-14 and those anticipated in the years 2018 and 2022, during which detector upgrades occur. Run I, Run II and Run III refer to periods of data-taking at ATLAS before and between the long shutdowns [11]. A maximum instantaneous luminosity of 7.7 times the standard $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ with center of mass of $\sqrt{s} = 8 \text{ TeV}$ was recorded for the 2012 over

CERN's accelerator complex

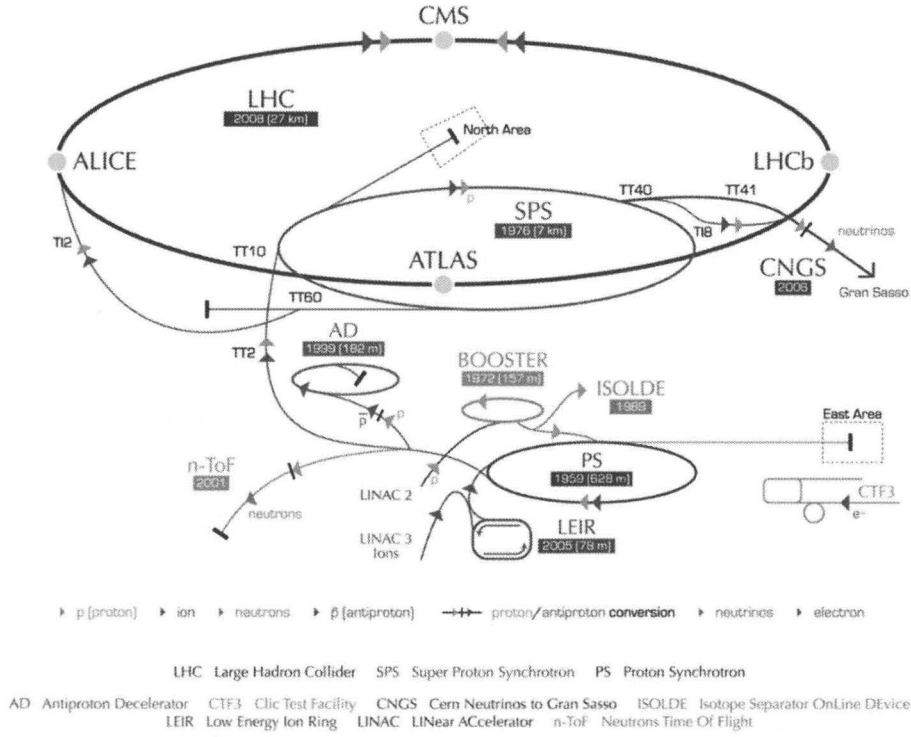


Figure 2.1: Schematic view of CERN's accelerator complex with the major 4 experiments ATLAS, CMS, LHCb and ALICE, and other connected accelerators.

Run I.

The LHC also accelerates and collides, in addition to the pp collisions, heavy lead-ions at energies roughly double those of any previous collider experiment, i.e. before Run II in the year 2015. These lead ions allow LHC experiments to investigate states of matter as they existed shortly after the big bang, reaching temperatures of several trillion degrees celcius [12]. The recorded luminosity and center of mass energy for Run II are $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\sqrt{s} = 13 \text{ TeV}$ respectively [13]. Phase-I upgrades in 2019 are anticipated to increase the luminosity to approximately three times the value of those from the previous run. Phase-II upgrades are expected to reach a design center of mass energy of $\sqrt{s} = 14 \text{ TeV}$ and increase the peak luminosity seven times by the year 2023 [14].

2.2 The ATLAS experiment

At the center of one of the LHC's collision points is the ATLAS experiment. This is a multi-purpose detector designed to take advantage of the full discovery potential of the LHC by directly detecting charged and neutral particles resulting from the

decay of unstable SM particles such as the Z and the $W^\pm$ boson, the recently discovered Higgs boson, and other particles hypothesized by other theories outside (and beyond) SM [9]. With cylindrical dimensions 46 m in length, 25 m in diameter and a weight of 7000 tonnes, it is, at present, volumetrically the largest detector ever constructed for a particle collider.

The co-ordinate system employed by ATLAS [15] is one where the interaction point is set at the origin, the z -axis set along the beam axis and the perpendicular x - y plane defining the transverse plane about which transverse momenta, p_T , is observed. θ is the polar angle measured from the z -axis to the $x - y$ plane, but in ATLAS the complementary angle η is used as defined in equation 2.4. Subsequently, the radial distance between the beam and the event is defined as r and ϕ refers to the azimuthal angle around the beam axis. Inside the LHC, two particle beams are made to collide at strategic points relative to the experiments and detectors. The rate of particle production due to pp collisions is measured by R , according to relation 2.1, where σ represents the cross-section for the particles in question and L the luminosity defined by the beam parameters as in relation 2.2.

$$R = \sigma L \quad (2.1)$$

$$L = \frac{1}{4\pi} \frac{N^2 f}{\sigma_x \sigma_y t} \quad (2.2)$$

$$\eta = -\ln \left(\tan\left(\frac{\theta}{2}\right) \right) \quad (2.3)$$

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad (2.4)$$

For this relation, N is the number of protons per bunch, f is the fraction of bunch positions containing protons, t is the time between bunches and σ_x and σ_y are the transverse dimensions of the Gaussian beam profiles. These parameters are optimised to obtain a satisfying production rate for the processes of interest. The cylindrical detector covers an angle of 2.5η , given in psuedo-rapidity units η defined by expression 2.3, with θ being the positive angle of elevation from the beam axis. Using the above, the spacial properties between any two objects is measured by ΔR , defined by relation 2.4

The detector system operates as a composition of numerous distinct sub-detector

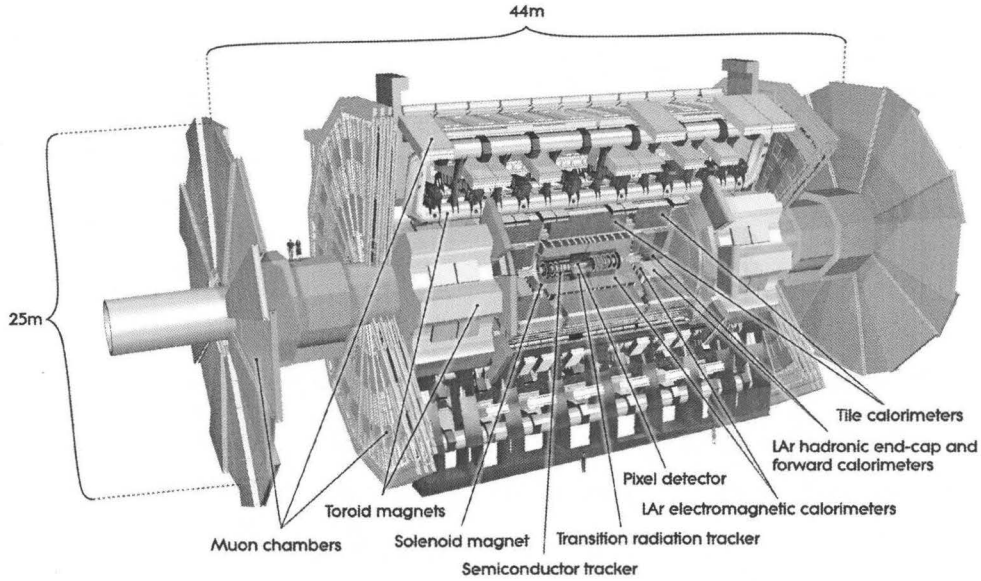


Figure 2.2: The ATLAS detector system.

systems, at varying locations (figure 2.2), for the implementation of different detection techniques. These sub-detectors are organized into three major concentrically wrapped components, about the point of collision, to record particle trajectories, energies and momenta. These components are the inner detector, calorimeter system and muon spectrometer. The detector system operates in a high magnetic field system for the bending of charged particles. The change in trajectory is, by electrodynamics, proportional to the momentum of the particle being detected, and is another means of energy determination. Integral in the setup of the detector and its components are the TDAQ system which selects physics events with distinguishing characteristics, and the computing system which develops and improves computing software used to store, process and analyze large amounts of collision data at 130 computing centers worldwide. A brief overview of the detector components shall be discussed in the subsequent sections of this chapter.

2.2.1 Inner detector

The inner detector is built of very compact and highly sensitive components [16]. It is the first layer of the ATLAS detector system for the observation of collision decay products from the LHC. This sub-detector measures the direction, momentum, and charge of electrically-charged particles produced in each pp collision. It consists of three distinct sensory systems in the presence of a magnetic field parallel to the beam axis as depicted in figure 2.3. These systems are the pixel detector, semiconductor

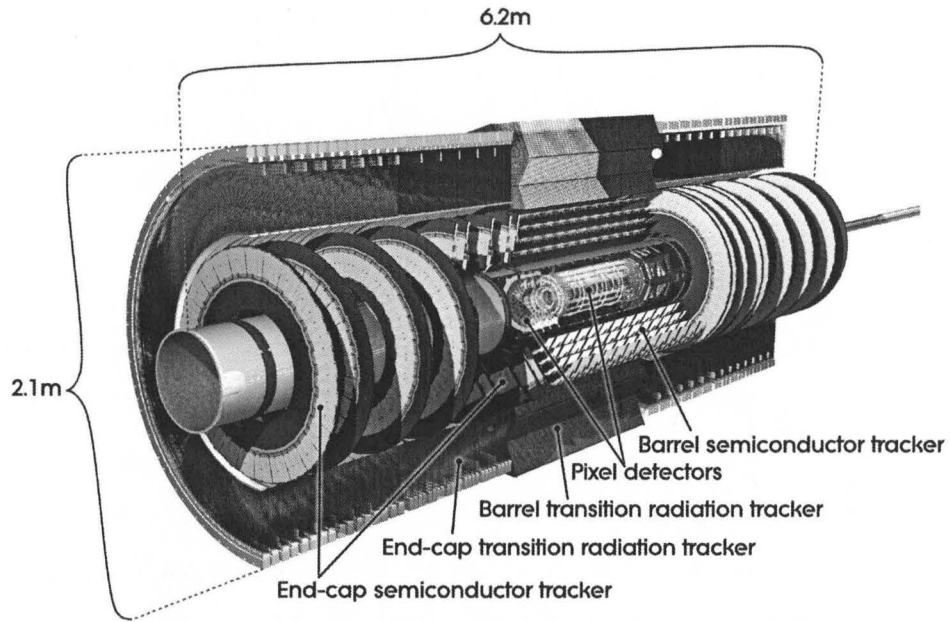


Figure 2.3: A slice cross-section of the ATLAS Inner detector.

tracker (SCT) and transition radiation tracker (TRT) [16] shown in figure 2.4. This detector is not of notable importance for the understanding of this dissertation, and shall not be discussed in great detail.

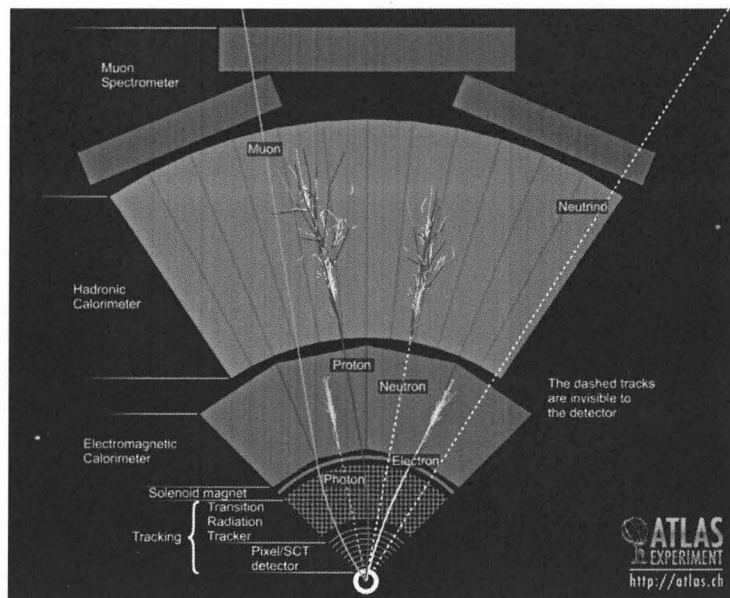


Figure 2.4: A cutaway cross-section of the ATLAS sub-detectors at various layers.

2.2.2 Tile calorimeter

Electromagnetic calorimeters are used in measuring the energy of photons and electron by virtue of their interaction with matter. The ATLAS sub-detector calorimeter system is designed to either stop or absorb most particles expelled from collisions in

the LHC. High-density passive absorbing materials such as lead, in alternating layers with active media such as liquid argon, force particles traversing through them to deposit their energy within the detector through nuclear interactions. The energy sampling of hadrons - i.e. particles containing quarks such as neutrons and protons - is done by hadronic calorimeters through the interaction of these hadrons with the nuclei of the absorbing material in the calorimeter. Analogously, the energy of electrons and photons is sampled by electromagnetic calorimeters. The ATLAS calorimetry systems consists of the liquid argon (LAr) calorimeter [17] and the tile hadronic calorimeter, known as TileCal, as shown in figure 2.6. For the sake of completion, it should be noted that the ATLAS calorimeter system is non-compensating, meaning the detection response due to the energy deposition from a hadronic shower and electromagnetic shower is not the same and has to be corrected by virtue of off-line software.

TileCal has a coverage of $|\eta| < 1.7$ and consists of a central long barrel and two sheathable barrels depicted as “Tile barrel” and “Tile extended barrel” on figure 2.6 respectively. These barrels are comprised of 64 modules with individual coverages of $\phi = 0.1$ and made from a series of 4 mm steel plates enveloping plastic scintillators 3 mm in thickness, placed transverse to the beam axis (refer to figure 2.5). The sandwiched scintillating tiles are made of polystyrene, and the radiation conditions they experience are the drive for the investigation of radiation damage.

High-energy hadrons from the collision traverse the detector, interacting with the enveloping steel plates, discussed in greater detail in section 3.3.3. This results in energy showers with the calorimeters, absorbed by the scintillator plates and emitted as fluorescent light. Fluorescence, and the photo-emission of organic molecules, shall be discussed in greater detail in section 3.3.

2.2.3 Muon spectrometer

Owing to their momenta, muons usually pass through the inner detector and calorimeter undetected (refer to figure 2.4). The Muon spectrometer, shown in figure 2.7, is the outermost part of the ATLAS detector. It does not stop the muons, but rather measures their momenta and records their trajectories. With the use of an average toroidal magnetic field of 0.6 T, it bends the muon trajectories allowing the determination of the particles’ momenta and energy from the curvature of the trajectory of the muons. To distinguish between cosmic muons and those from the

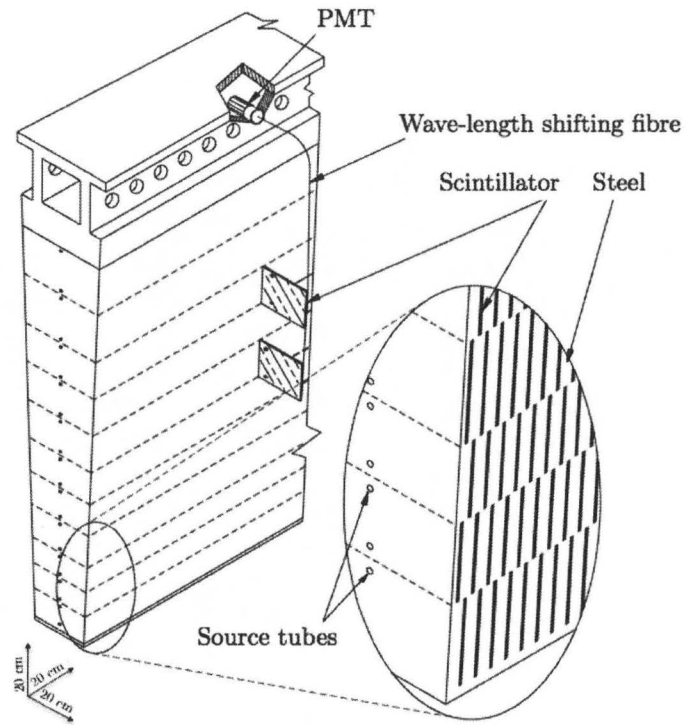


Figure 2.5: The TileCal read-out module as adapted from [18].

LHC collisions, only particles seen by other detectors first are considered. The muon spectrometer system has four different technologies at it's disposal, namely *thin gap* chambers (TGC), resistive plate chambers (RPC), monitored drift tubes (MDT), and cathode strip chambers (CSC) [19, 20].

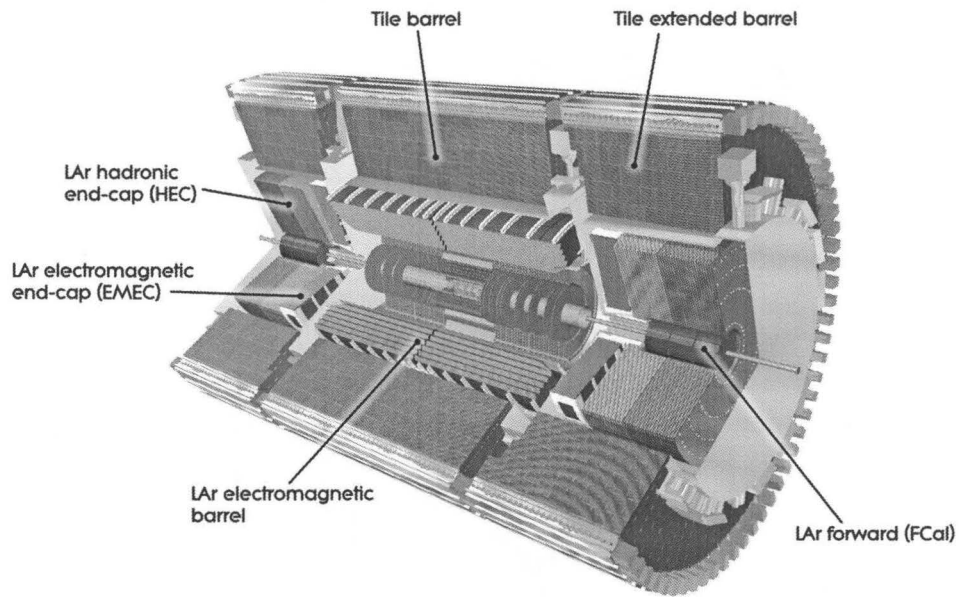


Figure 2.6: The ATLAS Calorimeter system.

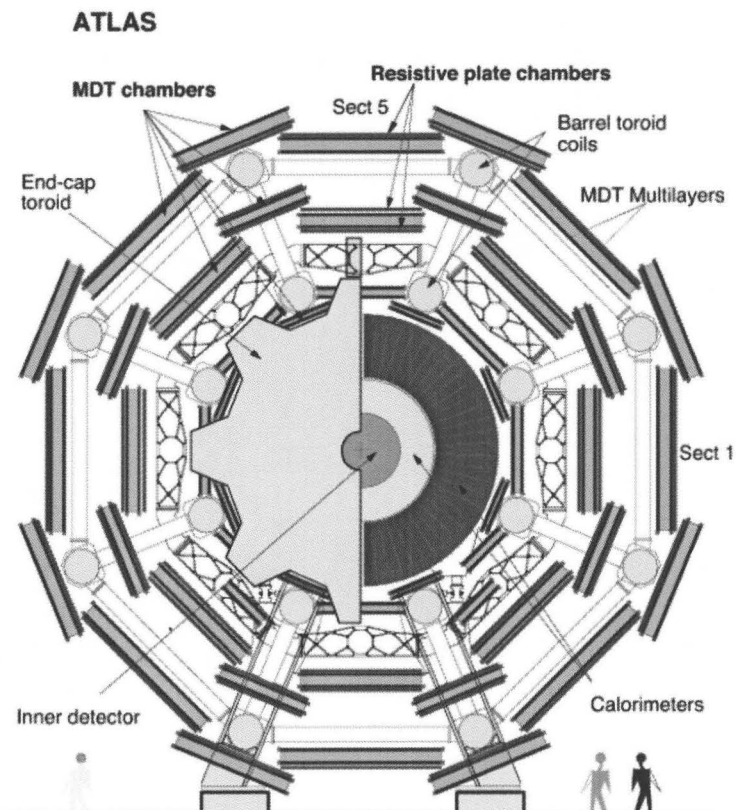


Figure 2.7: The ATLAS muon spectrometer as seen in a schematic cross-section.

Chapter 3

Radiation damage studies on plastic scintillator UPS 923A

3.1 Introduction

Dependent on the properties of the incident particles and the target, a fuller understanding of particle detection is one that rigorously encompasses the molecular and nuclear interaction between both media. In the case of plastic scintillator UPS 923A, the influence of radiation damage on the molecular structure of the plastic is investigated through the changes in the optical properties of the material. A deeper understanding of the changes in the plastic scintillator's optical properties has direct implications on Higgs boson analysis, owing to the scintillator array in the TileCal readout module as seen in figure 2.5.

The scintillator can undergo damage by nuclear interactions between its polymer base and the incident particles, neutrons in the case of this experiment. In this chapter, the scintillation process is discussed comprehensively and radiation damage is explained within the context of the experiments conducted. Radiation damage from energetic particles is already a topic of discussion [1, 21]. The nature of radiation damage is, however, convoluted [22] and a seemingly simple approach is necessary for a more comprehensive appreciation and understanding of the damage. At the junction on nuclear science, photonics and chemistry, the interdisciplinary nature of this work as expressed by Orville L. Chapman “often has been characterized by lusty, vigorous action rather than by law and order” [23].

A vast majority of plastic scintillators are a triplex of three components: a poly-

meric matrix that is the bulk of the material, a primary fluorescent additive that serves as the main source of light emission, and a wavelength shifter often referred to as a secondary additive. In the case of UPS 923A, polystyrene is the bulk material or base, PTP (p-terphenyl) is the primary additive and POPOP (5-phenyl-2-[4-(5-phenyl-1,3-oxazol-2-yl)phenyl]-1,3-oxazole) is the wavelength shifting additive [24]. Understanding neutron radiation damage on the optical properties of UPS 923A requires the following: an in-depth idea of the types of interaction mechanisms and energy transfers between the incident neutron and UPS 923A (section 3.3), familiarity with the optical properties of the material (section 3.3.1), the characterisation of radiation damage pertaining to the experiments (section 3.3.3), a discussion around the changes observed in the properties undergoing said damage (section 3.4) and a conclusive relation between the constituents of UPS 923A and the observed changes in the optical properties (section 3.5).

3.2 Detection of particles and their interaction with matter

The very nature of detection is dependent on the mechanisms that govern the interactions between the incident particles on the detector material and the material itself. Detectors work as transduction¹ machines that convert incident radiation energy (mostly kinetic) into other forms such as electrical energy. The primary mechanisms for this energy transfer are usually the excitation or the ionization of the target material by the incident radiation. Ionization detectors such as gas and semiconductor detectors determine the radiation signal by the presence of primary and secondary ions produced in the target material. In the case of excitation detectors, like TileCal, the interaction between the radiation and the target material causes the excitation of the molecules and atoms of the target material. The de-excitation process that follows results in the emission of photons corresponding to the excess energy of the excited atom or molecule, proportional to the incident energy deposit. The produced photons can then be converted into electric signal using a photomultiplier tube (PMT). The PMT is comprised of a photocathode made of a metal or alloys of metals with a low work function, as it will be described later, followed by a series of strategically located electrodes (known as dynodes) where cas-

¹Transducers are devices that convert some physical quantity (such as kinetic energy) into an electric signal

cading secondary emissions occur. The photocathode works on the principle of the emssioh of the outermost electrons of an atom by the absorption of photons known as the photoelectric effect according to the relation $E = hv - w$ where E is the energy of the photoelectron, hv is the energy of the incident photon or light where h is Planck's constant and v is the light's frequency, and w is the energy required to release the electron from the lattice, formally known as the work function [25].

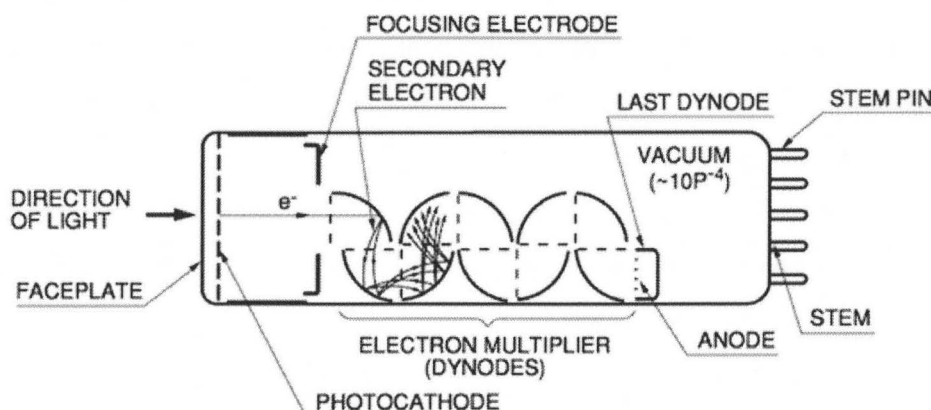


Figure 3.1: A schematic diagram of the components of a photomultiplier tube (PMT) [26].

As seen in figure 3.1, the electrons are focussed onto the dynodes by an electric field accelerating them from the surface of the cathode towards the primary dynode. There, they produce a number of secondary electrons. These are then accelerated to the next dynode, and the process is repeated. There are tens of multiplication stages before the charge is collected at the anode. The number of collected electrons is therefore proportional to those emitted from the cathode, and the number of those proportional to the intensity of the incident photons.

Plastic scintillators used for detection of ionising radiation generally contain some variation of an cyclic planar molecule with a ring of resonance bonds, known as aromatic ring structures, consisting of benzene-ring derivatives, giving rise to a delocalized π -electron² structure. According to the predictions of molecular orbital theory and the bonding and anti-bonding of molecular orbitals, the six atomic orbitals present in benzene have six associated molecular orbitals - three bonding π and three anti-bonding π^* , resulting in three transitions $\pi \rightarrow \pi^*$ [27]. These transitions have band associations corresponding to 180 nm, 200 nm and 256 nm, falling in the ultraviolet-visible range [28] which correspond to energies of roughly 7 eV, 6 eV and

²A π -electron in an electron in a π bond - a covalent bond in chemistry where two lobes of one atom overlap with two from another bond and each atom having an atomic orbital of zero at the nodes. Consult appendix section A.1 for orbital explanation

5 eV, respectively. When ionising radiation is incident on the scintillator material, part of the energy from the incident particle may be absorbed by the π -electrons.

3.3 Plastic scintillators

Organic scintillators (under which plastic scintillators fall) consist primarily of organic fluors suspended in a polymer base, as explained in section 3.2. The delocalized π -electron structures within the plastic molecules absorb some of the incident particle's energy, with the absorption exhibited typically within the higher energy visible spectrum and lower energy ultraviolet (UV) region - due to π -electron singlet state excitation. The energetic (excited) electron may return to its ground state through a number of processes as shown in figure 3.2, the most likely being those with the shortest lifetime of the excited state.

The energy transferred from the incident particle results in the excitation of the aforementioned electron. The resulting emission of photons from the de-excitation of the energetic electron is known as luminescence. The characteristic of luminescence is the emission of photons with less energy than the one absorbed because of the energy states of the orbital electrons. Luminescence is the result of two distinct forms of photon emission, namely fluorescence and phosphorescence (refer to figure 3.2 for the visual representation).

Fluorescence is defined as the spontaneous emission of light through the transitioning of electrons from a singlet excited orbital state to a singlet orbital ground state [29], with a different spin orientation for the pair of electrons. Phosphorescence is defined as photo-emission from a triplet state transitioning excited electron to a singlet ground state. The electron pairs exhibit the same spin orientation resulting in a longer decay time than that of fluorescence [30].

The de-excitation from lower excited states, such as T_2 , T_3 , S_2 or S_3 ³, to their lower energy states occurs within the same spin state (triplet de-excites to triplet and the converse for the singlet state) through internal conversion. This happens over a timespan of the order of picoseconds. This form of de-excitation is non-radiative and typically occurs when the excited states have relatively close energy levels (such as T_{13} and T_{14}) and have overlapping vibrational modes. The energy of the molecule is lowered through the molecule reaching thermal equilibrium after heat dissipation resulting from the collision of the vibrating atoms.

³ S_n and T_n refer to the n th singlet and triplet state respectively. See appendix section A.1

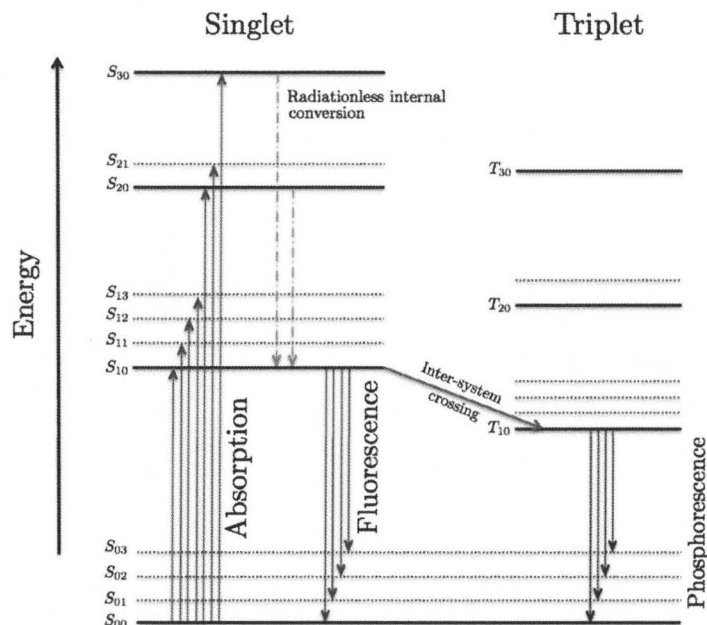


Figure 3.2: A diagram showing the energy levels of an organic molecule with π -electron structure [31].

Fluorescence occurs when electrons occupying the lowest vibrational first excited state S_{10} transition to the ground state as shown in figure 3.2 and photons of quantized frequencies are emitted. This process occurs over nanoseconds [32].

Inter-system crossings are the transitions of excited singlet states to triplet states. These occur over a longer time period. The T_{10} triplet state has a longer lifetime than the S_{10} singlet state, resulting in a delayed photon emission process known as phosphorescence. The frequency of the light from fluorescence is higher than that from phosphorescence. Another possible mechanism for energy depletion is delayed fluorescence. This is caused by molecules in the first excited triplet state undergoing radiationless transition to the first excited singlet state. This is due to the population of the first excited singlet state through the interaction of two molecules in the triplet state (also known as triplet-triplet annihilation) resulting in the production of one molecule in the excited singlet state. **Another cause is the population of the excited singlet state through the recombination of radical ions⁴ with electrons or from oppositely charged radical ions recombining [30]. The absorption energy of the molecules is larger than that of the fluorescent light because absorption changes the atom's internuclear potential's equilibrium, while the emitted light is a de-excitation (as discussed) to any ground state vibrational level [33]. There is a marginal overlap**

⁴Radicals are typically highly reactive and short-lived molecules

between the two energies for plastic scintillators, resulting in the re-absorption of the fluorescent light. Most plastic scintillator bases, without additives, are opaque to their own scintillated light and have low fluorescent yield (see section 3.4.2 for experimental results). Additives, called primary and secondary fluors, are added to increase the fluorescent yield of the plastic scintillator. These are typically added in small concentration, typically two orders of magnitude smaller by weight. Primary fluors, such as p-terphenyl in the case of UPS 923A, have an absorption spectra equal to the emission spectra of the base and yield more transitions for energy transfer [24]. A non-radiative form of energy transfer arising from coulombic interactions, known as Forster energy transfer [34], is another mechanism for the transfer of energy between the base and fluor. This results in the emission of light by the fluor across the low frequency ultraviolet region, typically around 350 nm. Secondary fluors are added to the bulk material as wavelength shifters. This not only changes the wavelength of the primary fluor such that it is not re-absorbed, but it also increases the bulk attenuation length of the light prior to being observed by the photomultiplier tube (PMT) [33].

3.3.1 Optical properties of plastic scintillators

Plastic scintillators are used as detectors due to their luminescence, defined in section 3.3 as the combination of two distinct photon emission mechanisms. The use of plastics scintillators for detection therefore relies on the understanding of the radiation in question and familiarity with photonics. Although the disciplines under which they are used and the reasons for their use are largely varying, the fundamental reason for the use of plastic scintillator detector setups is for radiation measurements. From a medical perspective, scintillators are used for, but not limited to, quality assurance testing of electron beams [35] which is crucial for safe and effective radiation therapy.

In high energy physics, the optical properties of plastic scintillators are employed for particle energy detection. The optical properties studied in this radiation damage experiment were the light yield, luminescence and transparency. Light yield is a measure of light output resulting from ionising radiation. This is done with some electronic and data acquisition rigour, and the results show histograms of charge intensities. Luminescence is the measure of how much light is observed due to irradiation, with some bearing on the transparency of the material and how the emitted

photons are reabsorbed within the material or are detected outside the bulk medium. The results give the emission spectra of the plastic. Transparency is the measure of light transmission through the sample in question over varying wavelengths. It shall be observed, for luminescence and light yield studies, that transparency is an intrinsic quality influential in any optical experiment. This shall be discussed more in section 3.5.

3.3.2 Neutrons and their interaction with organic molecules

Neutrons are uncharged so their interactions with matter are non-coulombic. Their energy transfers with matter are therefore a result of elastic collisions with the nuclei of the target material. As a result of this interaction, fast neutrons⁵ typically transfer their kinetic energy to light nuclei such as the hydrogen atoms in organic molecules. These reactions are, however, not a crucial energy loss mechanism and, as opposed to their occurrence, the energy transfer to the target material is through the agency of charged particles [36]. By understanding the interactions between neutrons and polymers, and the kind of damages exhibited in these polymers (see section 3.3.3 for the characterization of this damage), the observed changes in the measured quantities of the irradiated polystyrene based sample UPS 923A shall be some myriad of these interactions.

The formation of continuous altered atomic and/or chemical characteristics, known as “tracks”, and excited species within the target material is a general overall result of ionizing radiation absorption, irrespective of the type of incident radiation. Loosely speaking, the type of incident radiation on the material influences the properties of the excited product within the material. The chemical changes observed within the material are dependent on the total absorbed dose and are effectively independent of the type of radiation, except for fast neutrons. The four ionizing radiation types considered in varying rigour are fast and slow neutron radiation [37] which encompass the bulk of the analysis, electromagnetic radiation such as γ -rays and charged particles such as protons.

For charged particles, electronic excitations, ionization, nuclear reactions, elastic and inelastic scattering may all occur at ranging probabilities [38] as a result of electromagnetic and nuclear interactions [39].

⁵Fast neutrons are neutrons with a kinetic energy in excess of 0.1 MeV

Neutrons and electromagnetic radiation, being uncharged, primarily impart their energy by elastic and inelastic collisions and nuclear reactions. When incident on organic polymers, they interact to produce charged particles (bound electrons removed from bonding and non-bonding orbitals). The observed effect of the irradiation may therefore be similar to that observed from charged particles, irrespective of the type of radiation. The maximum fraction of transferable energy from the neutron to some nucleus of mass M is given by the relation

$$E_t = 4M/(M + 1)^2. \quad (3.1)$$

as seen in Tavenier's work [38]. For a hydrogen, carbon and oxygen atom $M = 1, 12$ and 16 respectively, and the maximum transferable energy ratios are $1, 0.28$ and 0.22 respectively. All the energy from the proton may be transferred to the hydrogen atom, and a smaller fraction is transferable to larger mass atoms, which results in the extraction of protons from the lattice [37].

3.3.3 Radiation damage characterization

The very process of radiation-induced luminescence - and, by extension, phosphorescence - is damaging to the plastic scintillator. This damage is rather complex, and arises from a myriad of atomic interactions. Studies on proton-induced radiation damage have investigated the formation of radicals in the molecular structure of the scintillator by performing computational density functional theory (DFT) electron paramagnetic resonance on small models of polymers [31] like those observed in plastic scintillators. Simply put, ionizing particles traversing through the scintillating material leave behind them broken bonds and altered polymer properties [40] at high enough doses⁶. These can be anything from hydrogen atoms and unpaired electrons to low molecular weight radicals. The damage experienced by the plastic may be dependent on the type of particles (or radiation) incident on the target [41], the radiation in which the plastic is being irradiated [42] and the radiation dosage amount and rate [43]. Changes in optical properties are crucial in detector physics, and any changes observed from these quantities may result in discrepancies on spectrographic analyses. These changes are a result of altered molecular structures within the scintillating material, particularly the benzene-ring fluorescent components, or

⁶The term *dose* is used quite loosely to mean the number of particles impinging on a surface. Refer to appendix section A.1 for dosage discussion

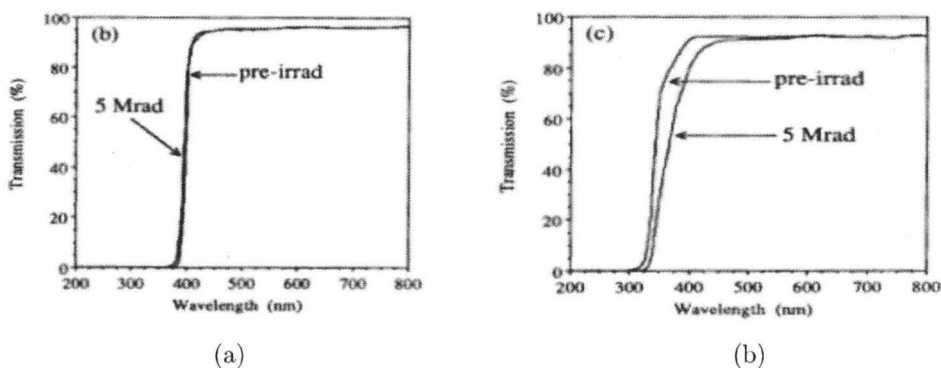


Figure 3.3: The Transmission spectra for the B505 sample (a) and for the undoped base of B505 (b) [44].

the degradation of transmittance caused by optical absorption zones.

Studies performed on liquid scintillator BC505 having been exposed to 5 Mrad⁷ from a 600 Ci⁸ Co-60 gamma source have showed that primary and secondary fluors used as dopants are generally quite radiation hard⁹ as observed in figure 3.3 [44].

The main component subject to radiation damage is, as seen from research on liquid scintillators, the base scintillating material. The undoped base exhibited notable losses in light output in response to the radioactive source, and decreases in transparency suggesting the formation of an absorptive front converging at lower frequencies. This absorption may extend to wavelengths over which radiative transfer between fluors occurs, competing with the material's light shifting mechanisms and reducing the scintillator's intrinsic light output. Mass quadrupole spectroscopy studies performed by Torrisi on high stopping power radiation, inducing radiation damage on PVT, showed a 50% decrease in the overall luminescence yield [43].

A number of processes are somewhat fundamental in the characterization of radiation damage as they alter the nature and extent of the damage in a myriad of ways. These are radical formation as a result of gas evolution, cross-linking and unsaturation, and oxygen exposure and recovery.

⁷The rad is a unit of absorbed radiation dose. See relation A.2 in appendix section A.1

⁸Ci is the (non-SI) unit for radioactivity. The *Bequerel* (Bq) is the SI unit of measuring radioactivity. 600 Ci is equal to $22.2 \cdot 10^{12}$ Bq

⁹Radiation hardness is a relative form of radiation damage resistance, generally defined contextually

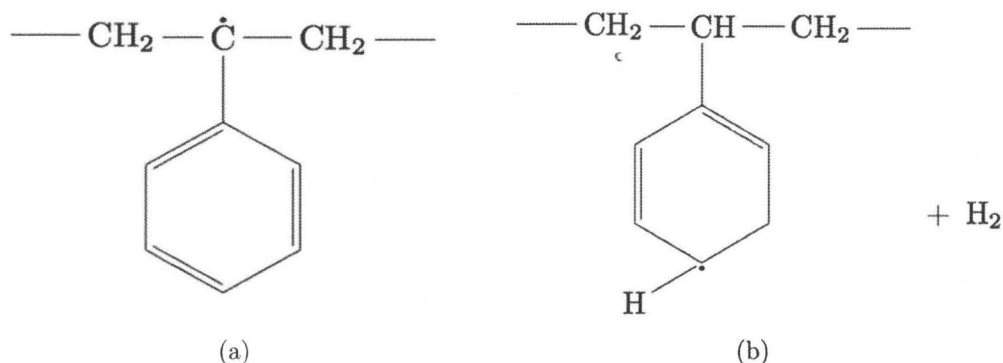


Figure 3.4: Benzyl radical (a) and cyclohexadienyl-type radical (b) [31].

Radical formation and gas formation

The breaking of bonds in long chains, also known as scission, ensue gas evolution. This results in either ion pairs or free radicals and unpaired electrons, dependent on the kind of bond severed. Hydrogen is commonly formed from the irradiation of plastics that do not contain any oxygen [37], primarily from the C-H bonds, and results in radical formation. Benzyl- and cyclohexadienyl-group free radicals are a common formation in polystyrene-based plastic scintillator damage as seen in figure 3.4. The former is a result of dehydrogenation from the styrene monomer leaving a carbon atom with an unpaired electron and the latter from the addition of a hydrogen to the styrene monomer resulting in the formation of hydrogen gas [37].

Cross-linking and unsaturation

Radicals, formed from the breaking of bonds by ionising radiation, form complex three dimensional networks [45]. These are covalent bonds formed between two or more polymer chains, and are referred to as cross-linking [46]. With increasing dose and damage, more chains are destroyed, the likelihood of forming these three-dimensional links increases which results in the discolouration of the plastic and there is an increase of carbon-carbon bonds $\text{C}\equiv\text{C}$ and $\text{C}=\text{C}$ [47] (unsaturation) from the dehydrogenation of C-H bonds as a from the evolution of hydrogen gas. New electronic transitions [48] and absorption bands [49] arise from the degradation of the polymer, known as 'colour centres.' These have undesirable ramifications in the optical properties of the plastic, investigated further in section 3.4.

Oxygen exposure and recovery

During the irradiation process, peroxide radicals and other oxygen products form in the polymer due to the diffusion of oxygen present in the air. The presence of these in the plastic reduce fluorescent light output as they act as quenching agents [50]. The diffusion of oxygen in the polystyrene forms peroxy activated complexes that further form radicals and other stable products such as hydrogen or carbon, and in environments containing oxygen (air) this results in $C=O$ and $C-H$ group products [51]. The formation of these products is dependent on many environmental factors, may continue even post irradiation and is primarily a function of temperature [52]. The scintillator may ‘recover’ a fraction of its fluorescence depending on the environment it is kept under and the absorbed dose it was subject to [53]. This process is catalysed by the presence of heat - a process known as annealing - and oxygen exposure.

3.4 Radiation damage testing

The influence of radiation damage on plastic scintillator UPS 923A was tested on the optical properties of the material, particularly transmittance, luminescence and light output (light yield). The damages discussed in section 3.3.3 - namely radical formation, cross-linking, unsaturation and oxygen exposure during and after irradiation - are the known causes of this damage. The changes observed in the optical properties shall allude to the kind of chemical and/or steric alteration to the molecular structure of the sample.

Irradiation of samples

The optical properties of Ukraine polystyrene-based plastic scintillator (UPS 923A) were tested by irradiating three of four identical UPS 923A samples of dimensions 20 mm × 20 mm × 6 mm (see appendix section A.1 for sample information) in channel 3 of the IBR-2 reactor [54], as seen on figure 3.5, at the Joint Institute for Nuclear Research.¹⁰

Figure 3.5 shows a cross-sectional schematic of the chamber used for irradiating the samples. As shown, the samples (3) are held in place for irradiation at position 1, with shielding at positions 4 and 5. A water moderator is seen at position 7, and

¹⁰The Joint Institute for Nuclear Research, or JINR, located in Dubna, Russia, is an international intergovernmental organization and research institution. [Click here for organization website.](#)

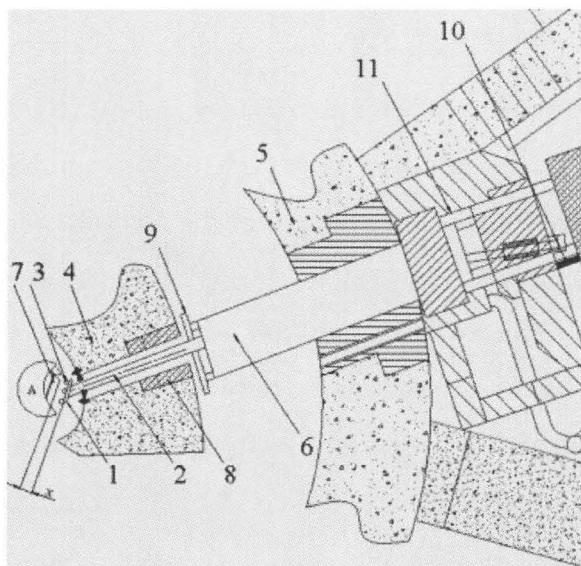


Figure 3.5: The irradiation facility: 1 – metallic container to hold the samples; 2 – transport beam; 3 - samples for irradiation; 4 – the first biological shield; 5 – the second biological shield; 6 – massive part of irradiation facility; 7 – water moderator; A – active zone of the IBR-2 reactor; X – the distance of moderator surface to the samples, 8 – shutter of biological shield; 9 – emergency stops; 10 – seen mechanical stop, 11 – rail way. All hatched elements on the figure are parts of the biological shield off the irradiation [54].

position 9 shows the emergency stops. The samples, placed as shown in figure 3.5, had fast neutrons of fluences $1.8 \cdot 10^{14}$, $1.7 \cdot 10^{13}$ and $3.8 \cdot 10^{12}$ neutrons/cm² impinging on them. This was achieved by positioning the samples at strategic distances from the neutron source where the average neutron flux on the samples was as mentioned. Figure 3.6 shows the distribution of the neutron fluxes at a fixed distance from the neutron source and the relative activity of Ni foil from the same distance. This shows the changes in neutron fluences as a function of distance. Note that the distance between the samples and the source and the distance between the sample and the moderator may be used interchangeably for relative qualitative expressions. The distance from the moderator is of no interest to the experimental analysis of the radiation damage, save for the dose absorbed by the samples at those distances. The neutron fluxes shall, therefore, be taken as absolute to some significance, and the distances between the samples and the moderator shall be done away with.

3.4.1 Transmittance studies

Transmittance refers to the ratio of light intensity (directly proportional to the number of photons) transmitted through a body to that incident or impinging on that body ($T=l/l_0$). In this study, changes in the light transmitting capabilities

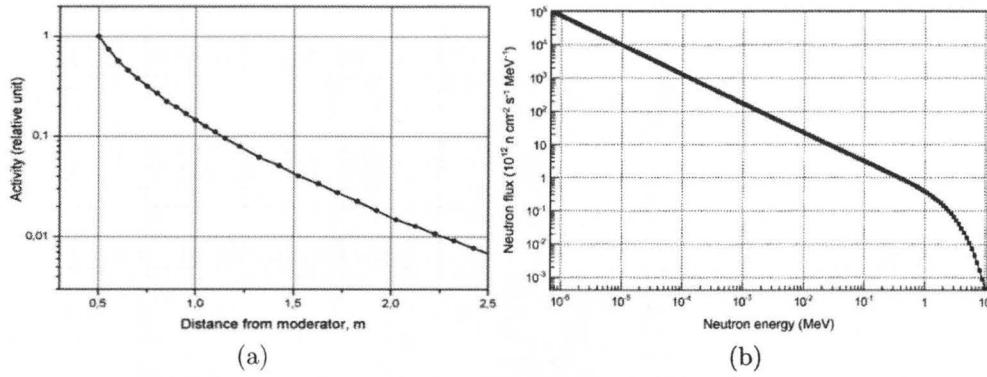


Figure 3.6: The neutron flux distribution at 0.3 m from the neutron source [54] showing (a) the neutron activity as a function of distance from the neutron source and (b) Ni foil relative activity 0.3 m from the neutron source.

of the plastic scintillator samples are investigated as a function of the radiation dose. The transmission of light through the samples is measured using a Shimadzu SolidSpec-2700DUV spectrophotometer. The objective of the study is to determine the changes to the “transparency”¹¹ of the samples. This is done to two ends, first for determining the samples’ transparency to certain wavelengths and, secondly, to quantify the changes in that transparency as a result of the radiation doses the samples were subjected to.

Apparatus and experimental setup

The transmittance studies were performed on the four samples using a Shimadzu SolidSpec-2700DUV spectrophotometer. Spectrophotometers, a specific kind of electromagnetic photometer, are devices used to quantitatively measure reflection or transmission properties of materials over the visible spectrum, the infrared region and (in the case of the Shimadzu SolidSpec-2700DUV) the ultraviolet (UV) region. The samples are placed inside a nitrogen purged chamber inside the spectrophotometer to eliminate oxygen molecules that absorb UV light under 190 nm. Inside the chamber, the samples are held in place such that the light beam is perpendicularly incident on the 20 mm · 20 mm area and traverses through the 6 mm thickness of each sample. The spectrophotometer uses two light sources, a 50 W halogen lamp and a deuterium lamp. The default light source wavelength is set to 870 nm, so no corrections for changes in light source are required for the transmittance studies.

¹¹Transparency is a generic term commonly used for the transmittance of visible light. In this case, it is used interchangeably with ‘transmittance’. The two shall be distinguished in the analysis section when the ratio of the irradiated samples’ transmitted light to the unirradiated transmitted light is investigated. Only later in the results section is transmittance shown and explained.

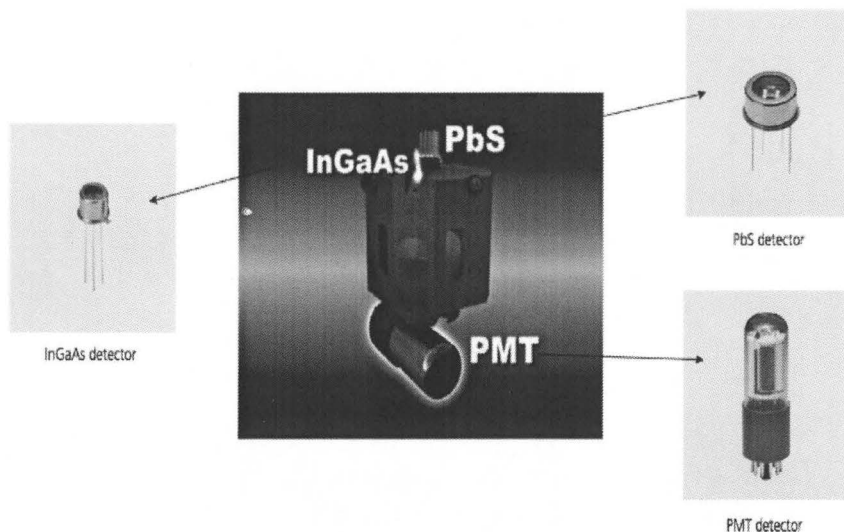


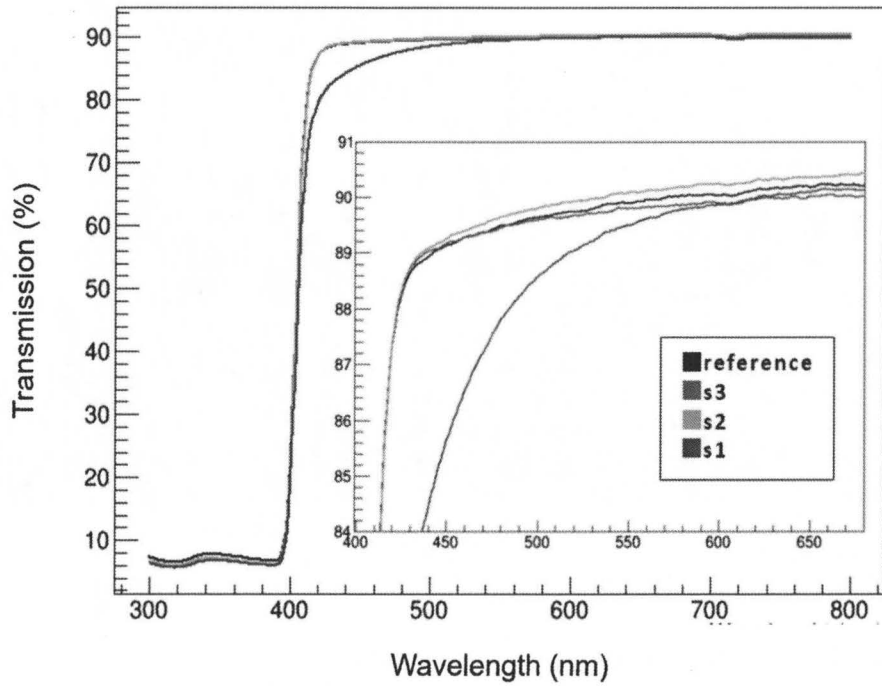
Figure 3.7: The integrating sphere of the Shimadzu spectrophotometer consisting of an InGaAs detector, PbS detector and the PMT detector components shown here separately and as a unit [55].

The transmitted light is detected by three detectors as seen in figure 3.7, all contained in the Shimadzu SolidSpec-2700DUV. For the transmittance studies, however, only the PMT is used due to the range over which the transmittance is determined. Once detected, analysis software groups the intensity of the detected light in ranges (or bins) as a fraction of the light produced by the sources through air (or nitrogen in the case of the oxygen purged conditions).

Preliminary results

The transmittance for this study is determined by the ratio of the detected intensity of light transmitted through the sample to the intensity of light detected without a sample (through nitrogen). This gives a result for each sample as shown in figure 3.8.

The spectrophotometer in use has a wavelength accuracy of ± 0.2 nm for the UV and visible region, the regions of interest for this study. Figure 3.8 shows the transmittance results for the four samples under study (s1, s2, s3 and the reference sample). The unirradiated or reference sample may be used as a benchmark for investigating the changes in transmittance. Any changes in the values and the shape of the transmittance plot observed in the cases of the other samples are quantitatively related to the reference for a qualitative analysis of the possible cause(s) as discussed in section 3.3.3. A more holistic discussion of each optical property tested and the possible causes is given in section 3.5.



(a)

Figure 3.8: Transmitted intensity per wavelength plot for the four samples where reference is the unirradiated sample (or sample 0), s3 (sample 3) irradiated at $3.8 \cdot 10^{12}$ neutrons/cm², s2 (sample 2) at $1.7 \cdot 10^{13}$ neutrons/cm² and s1 (sample 1) at $1.8 \cdot 10^{14}$ neutrons/cm².

3.4.2 Luminescence studies

Luminescence, for the intents and purposes of this study, is defined as the intensity of light emitted as a result of the excitement of the sample by a 244 nm laser. Like the light yield experiment, luminescence studies investigate the energy spectrum of the scintillator emitted light.

Apparatus

The laser used was a Lexel Model 95 SHG argon ion laser [56]. The setup, shown on figure 3.9, employed the use of a frequency-doubling crystal to generate 244 nm from the 488 nm laser line. The incident UV laser beam was focused onto the sample using a Thorlabs 20x UVB objective. The beam was scanned over a square of size $20 \mu\text{m} \times 20 \mu\text{m}$ to give some local averaging of the luminescence. The backscattered light was dispersed via a 150 lines/mm grating in a Horiba LabRAM spectrograph onto a liquid nitrogen cooled charge coupled device (CCD) for detection. The accumulation time of each spectrum was 1 second and acquired via LabSpec v5 software. Due to the sensitivity of the detection material to light, the experiment is

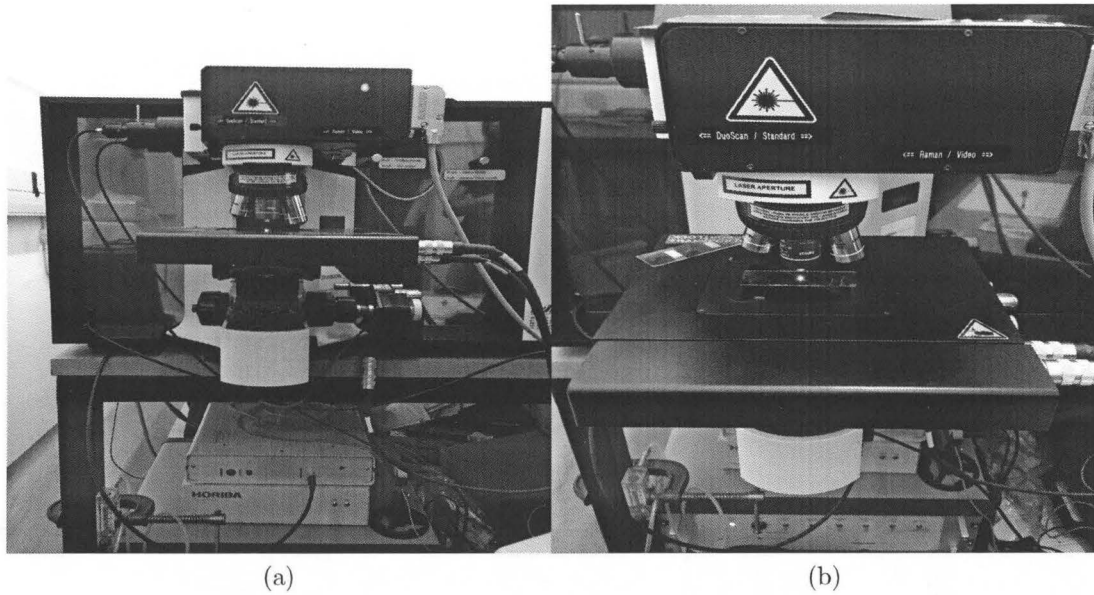


Figure 3.9: The luminescence experimental setup as seen from the front (a) and from an elevated front (b). Shown are the source of the laser, the laser aperture, the objective, the laser trajectory, the sample and the casing for the CCD.

conducted in a darkened room with no ambient light.

Results and analysis

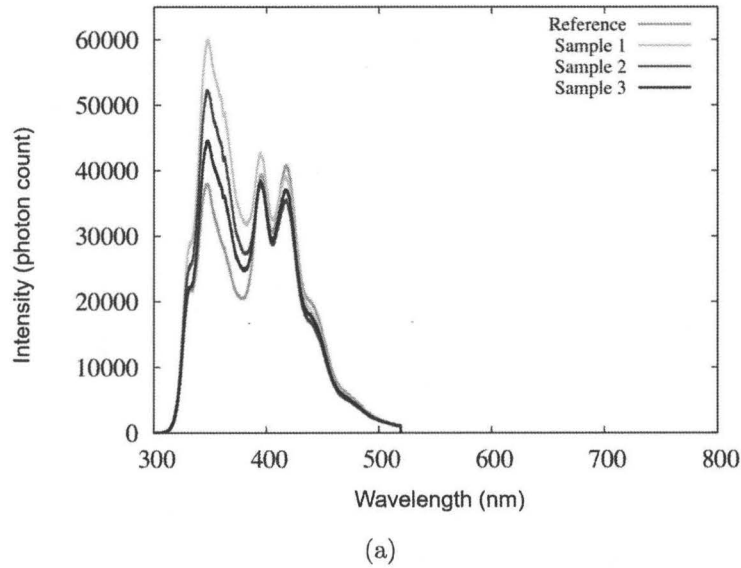


Figure 3.10: The luminescence of the 4 samples on the same axis, showing the intensity of the light (proportional to the number of photons emitted by the samples due to the laser) at the given wavelengths.

The data collected for the luminescence experiment were the number of photons per given wavelength over a time of 1 second. This, shown in figure 3.10, expresses the intensity of each wavelength for all three irradiated samples on the same set of

axes as the reference sample. From the figure, peaks in the spectra of the samples are observed at wavelengths corresponding to approximately 350 nm, 400 nm and 420 nm. These wavelengths are attributable to the low-energy UV/high-energy violet range for 350 nm, and the intersection between indigo and blue for 400 nm and 420 nm.

3.4.3 Light yield studies

There are a number of ways to quantitatively determine the light output of plastic scintillator samples. The light yield experiment is a study for the determination of the intensity of scintillation light as a function of radiation dose. While the transmittance study investigated the intensity of light traversing through the sample, and the luminescence study focussed on the energy spectrum of the light output as a result of electromagnetic radiation, the light yield study researched the light output intensity as a result of particle radiation incident on the sample.

Apparatus

The objective of the experiment is to investigate the scintillator light output or yield of each sample as a result of radiation damage due to ionizing particle radiation. The radiation is supplied by a Cs 137 beta (β^-) source of activity 3.215 TBq, placed above the plastic scintillator sample enclosed in a lightproof cap to stop ambient light interference. This placement is due to the small size of the cesium source relative to the sample. The plastic sample is placed in contact with a Hamamatsu R2059 PMT [57], connected to a high voltage power supply and a Keithley 6487 picoammeter [58] as shown in figure 3.11. For a more detailed schematic of the experimental setup, refer to section A.1 of the appendix. The picoammeter reads the current output of the PMT (directly proportional to the intensity of the light output from the scintillator) and relays the analogue signal to a PC where the current is binned in a histogram fashion by PC software.

Results and analysis

The current read by the picoammeter is relayed to the PC's data acquisition software. The frequency of each current value is then expressed on a histogram of bin size 10 nA.

Figure 3.12 shows the histograms expressing the distribution of current output

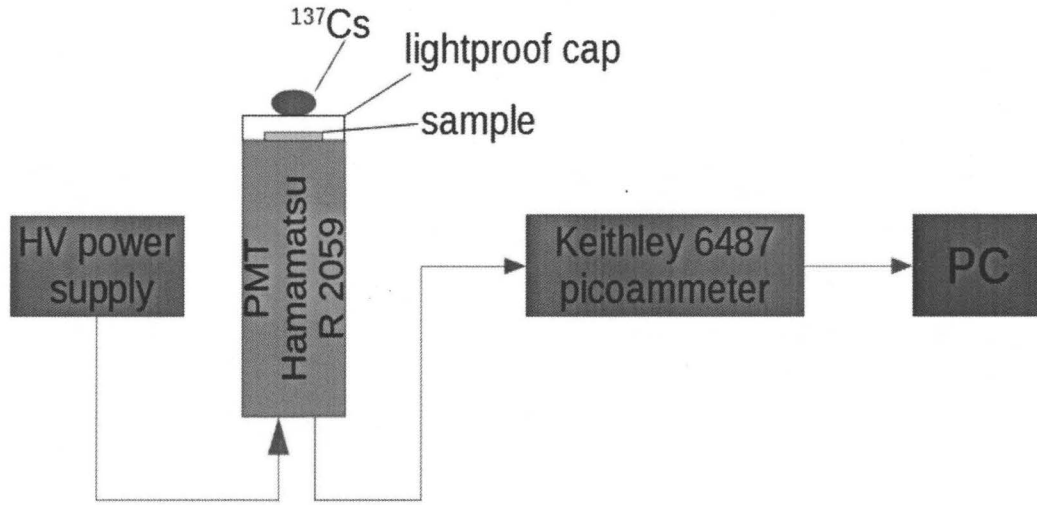


Figure 3.11: The schematic setup of the light yield experiment

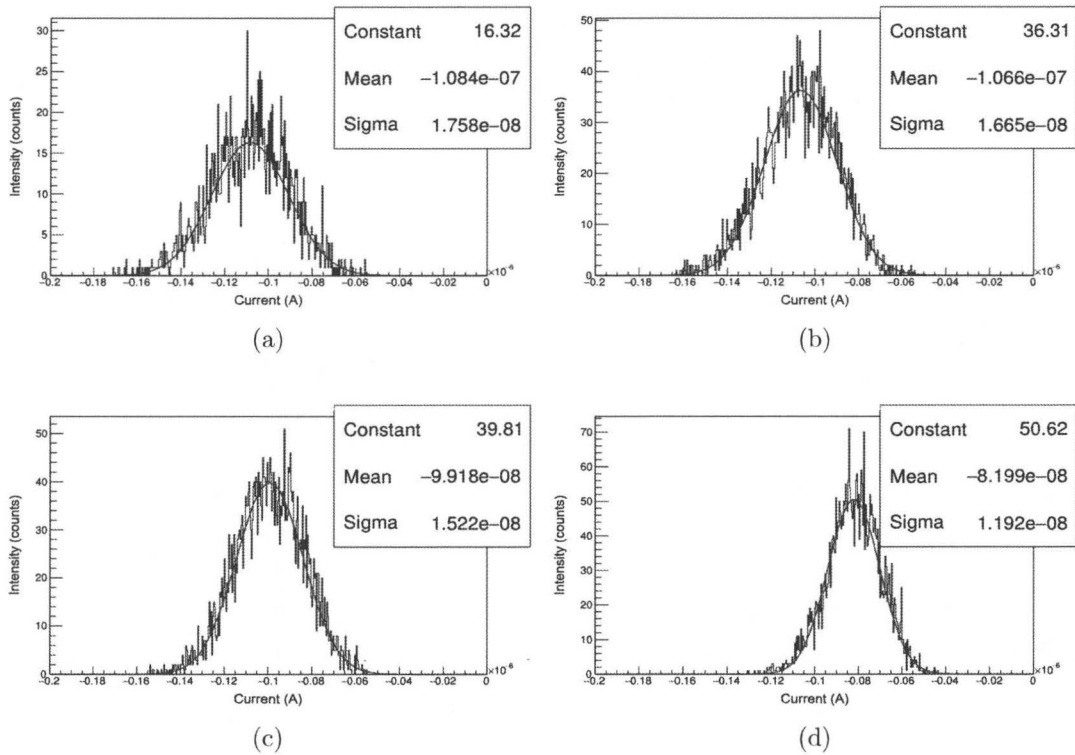


Figure 3.12: Histograms of the the light yield showing the frequency of each current value per sample with a Gaussian distribution fit. The plots are for (a) the reference or unirradiated sample, (b) sample 3 irradiated at $3.8 \cdot 10^{12}$ units, (b) sample 2 irradiated at $1.7 \cdot 10^{13}$ units and (d) sample 1 irradiated at $1.8 \cdot 10^{14}$ units. Each unit represents a neutron per cm^2

for each sample as read by the picoammeter. The Gaussian fit imposed onto the data allows the use of Gaussian quantitative values such as the mean, standard deviation (sigma) and constant for analysing changes in the light yield as a function of radiation dose. These serve as a representation of the mean current received by the

picoammeter resulting from the photons emitted during the irradiation of the samples by the cobalt source. The absolute of the mean current is directly proportional to the number of photons emitted by the scintillator during the beta irradiation process. The above Gaussian fits are then superimposed on one plot (figure 3.13) for a relative representation of the current output. These currents, directly proportional to the intensity of the photons detected by the PMT, serve as a proportional representation of the light output of each sample from particle radiation. A noteworthy observation is the decrease in the absolute mean current with increasing radiation dose as seen in figure 3.13.

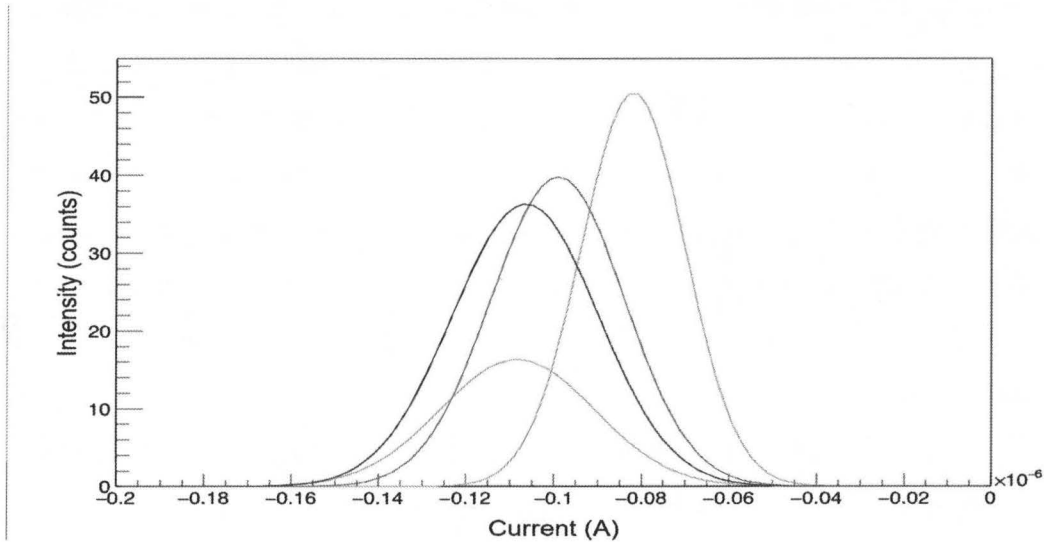


Figure 3.13: Gaussian fits for the four samples superimposed on the same set of axes. Green represents the reference or unirradiated sample, blue represents sample 3 irradiated at $3.8 \cdot 10^{12}$ units, red represents sample 2 irradiated at $1.7 \cdot 10^{13}$ units and grey represents sample 1 irradiated at $1.8 \cdot 10^{14}$ units. Each unit corresponds to a neutron per cm^2

3.5 Discussion

Radiation damage studies are a myriad of physical interactions and chemical alterations. These are crucial for the ATLAS experiment, as the TileCal is comprised of a high number of these plastic scintillators under study. In this study, the basic mechanisms governing detection were highlighted (section 3.2) as an introduction to plastic scintillators (section 3.3).

This chapter investigated particle interactions with matter and how these particles are detected, with a focus on neutrons and their interaction with scintillator organic molecules. The characterization of radiation damage is discussed, leading to how

this damage affects these scintillators and their optical properties. Experiments performed on plastic scintillator UPS 923A are discussed extensively, from the apparatus to the results.

From the results on the three irradiated plastic samples (sample 1, sample 2, and sample 3), the transmittance studies show a notable transmission decrease with increasing radiation dose. This decrease in transmission, seen at wavelengths above 400 nm, shows most prominently for sample 1 (having the highest irradiation dose at $1.8 \cdot 10^{14}$ neutrons/cm²), showing an approximately 5% decrease (as seen from figure 3.8) in transmission from 89% to 84%. Changes in transmission allude to changes in the mechanisms governing transparency - such as the resonant frequency of the material and its chemical constituents. Radical formation and cross-linking, discussed in section 3.3.3, from the scission of long chains, may create zones of altered chemical properties. These zones can be a myriad of chemical combinations as simple as hydrogen [37] to complex three-dimensional networks [45] consisting of benzyl- and cyclohexadienyl-type branches, to mention a few. These radicals, known to quench fluorescence [59], are viable candidates for the transmittance decrease in the irradiated samples' case.

From figure 3.10, peaks in the spectra of the samples are observed at wavelengths around 350 nm, 400 nm and 420 nm. These wavelengths are attributable to the low-energy UV/high-energy violet range for 350 nm, and the intersection between indigo and blue for 400 nm and 420 nm. This explains the purple/blue colour observed when the laser is shone on each sample.

Comparing each of the three irradiated samples to the reference (see figure 3.10), the 350 nm peak is seen to move in the direction of increasing intensity with increasing irradiation dose, that is, from sample 3 to sample 1 with intensities of approximately 6000 to 4500 photons, respectively. Tempting as it may be to credit this change to radiation damage, it is important to note the absorption and emission spectra of the base and the doping components of the scintillator. Polystyrene, the base of the scintillator, exhibits absorption at approximately 270 nm at concentrations used in this experiment [60] [61]. While PTP and POPOP, the primary additive and the wavelength-shifting additive respectively, exhibit absorption at 380 nm [62] and 358 nm [63], the combination of the additives' absorption spectra and the observed peaks in figure 3.10 suggests that the luminescence experiment yielded no conclusive changes in luminescence arising from radiation damage. The marginal changes such

as the positive shift in the emission wavelength at 350 nm suggest changes on the surface of the scintillator material (where little to no absorption occurs) under the assumption that the concentration of the additives is even throughout the sample(s). This may be arrived to due from observing the shape of the spectra, which is similar save for the move in the direction of increasing intensity. A change in the structure of the base and/or the doping components of the scintillator governing the luminescence would be assumed to result in non-uniform changes to the three peaks.

In the case of the light yield studies, the Gaussian fit provided mathematical quantities such as mean and standard deviation for the analysis of the read-out current. The mean, crucial in the analysis of the light yield, represents the average current read for each sample. This mean current, proportional to the scintillator light output intensity, allows for comparative analysis between each sample pertaining to the mechanisms governing and influencing scintillation. As observed in figure 3.13, the reference sample curve (green) has the largest absolute mean, and sample 1 (purple) has the smallest. Sample 1, having been subjected to the highest radiation dose of $1.8 \cdot 10^{14}$ neutrons per cm^2 , had fewer (1) photon emitting processes and/or had (2) more zones of limited light transmission. The former (1) may be supported by the same rationale proposed in the transmittance studies, radical formation and cross-linking, which has a direct influence on the chemistry of the samples. In the luminescence studies, the bulk material could not be probed by the laser because of the absorption spectrum of the polymer base. If the alterations in the chemical structure of the sample influence the absorption spectrum of the material, even if marginally, a change in the light output will be observed. This change would be a viable candidate for (2) zones of limited light transmission. A clear change in the transmittance of the sample is observed as a function of the wavelength, where the highest irradiated samples show the largest change.

Chapter 4

The heavy scalar H production with $t\bar{t}$

Following the body of research after Run-I data [5], an effective field theory approach has been introduced for two additional real scalars, H and χ . This approach, and subsequent addition of the real scalars, serves as introductory steps in the study of the Higgs boson and its production with top quarks at the LHC. This, eventually, leads up to the substitution of the SM Higgs boson h with the 2HDM heavy scalar H decaying into the SM Higgs boson by $H \rightarrow h\chi\chi$. In this study, a benchmark scenario with parameters $m_H = 275$ GeV and $m_\chi = 60$ GeV is considered.

The search is performed in two stages; the first case reconstructs the top quarks and analyses event selections through single-lepton event selection criteria, and the other case studies same-sign leptons (electrons or muons) in dilepton events. Observables such as b and c -tagged jet multiplicities, total missing transverse energy E_{miss}^T and the total scalar sum of the transverse momenta all present jets and leptons shall be studied.

4.1 Model dependence

Leading up to the research on the decay of $A \rightarrow ZH$, studies on the production of the heavy scalar H were underway [64]. As seen in work done by the University of the Witwatersrand [5], studies predicting the transverse momentum (p_T) spectra of the SM Higgs boson (h) following an effective field theory approach with the addition of two real scalars H and χ have been introduced with the Standard Model (SM) Lagrangian $\mathcal{L}_{\text{SM}}$.

The process of interest in this study is the production of the heavy scalar H by gluon fusion through proton collisions according to $pp \rightarrow H \rightarrow h\chi\chi$, where χ is the dark matter (DM) candidate and source of E_{miss}^T . This study serves as a continuation of the analysis consisting of the measurements for the Higgs boson differential transverse momentum, double Higgs boson resonance searches, Higgs boson production associated with top quarks and VV resonances (for $V = W^\pm, Z$). The mass of the scalar H is measured at $m_H = 272_{-9}^{+12}$ GeV [5] on the basis of an efficient χ^2 analysis.¹ The mass of the χ is predicted to be 60 GeV. For this precursory study, the heavy scalar and DM candidate masses are taken as $m_H = 275$ GeV and $m_\chi = 60$ GeV respectively. The production modes of the Higgs boson are discussed in section 4.2 and its associated $t\bar{t}$ production is discussed in section 4.3.

4.2 Higgs boson production at the hadron colliders

Production of the Higgs boson at the LHC is achieved through three main channels. In decreasing order of cross-sectional magnitude, the modes are (1) gluon fusion through top quarks in single loops, (2) vector-boson fusion through $W^\pm$ and Z bosons and (3) in association with a pair of top-quarks and with a single top-quark. It is also known that the $h \rightarrow b\bar{b}$ final state is the dominant decay mode in the SM Higgs boson decay for Higgs mass $m_h = 125$ GeV yet has not, at the time of the completion of this analysis, been observed. The search for this decay mode has a significant multijet background in the gluon fusion process (1), but the ratio of signal-to-background for this decay mode can be improved via modes (2) and (3) [65]. For the studies presented, only process (3) is of importance owing to the direct measurement of the top-Yukawa coupling, y_t . Since y_t is close to unity due to the large mass measured for the top quark, $m_t \approx 172$ GeV, new physics searches occur in the same energy scale order of magnitude. This rationale asserts attention to studies of productions modes not only in association with the h , but with the inclusion of the comparatively heavy H .

¹ χ^2 refers to a statistical sampling distribution test and not the DM candidate χ introduced. Wherever ambiguous, clarity between the test and the particle shall be explicitly given

4.3 Associated Higgs production with top quarks

Construction of the effective field theory is achieved through a “bottom up” approach as introduced in previous work [5]. The code executing numerical analyses is written in MATHEMATICA, C++, PYTHON. Models are generated with FEYNRULES, further used for event generation through MADGRAPH5. Events are subsequently showered and hadronized using PYTHIA 8.2, plotting and analyses following through the employment of a RIVET package.

An effective Lagrangian approach

Consider two hypothetical real scalars H and χ , outside the SM spectrum of particles. The effective Lagrangian of a theory encompassing these particles can be written with the addition of terms to the SM Lagrangian $\mathcal{L}_{\text{SM}}$ as:

$$\mathcal{L}_H = -\frac{1}{4} \beta_g \kappa_{hgg}^{\text{SM}} G_{\mu\nu} G^{\mu\nu} H + \beta_V \kappa_{hVV}^{\text{SM}} V_\mu V^\mu H, \quad (4.1)$$

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} \left[y_{ttH} \bar{t}tH + y_{bbH} \bar{b}bH \right], \quad (4.2)$$

$$\mathcal{L}_T = -\frac{1}{2} v \left[\lambda_{Hhh} Hhh + \lambda_{h\chi\chi} h\chi\chi + \lambda_{H\chi\chi} H\chi\chi \right], \quad (4.3)$$

$$\mathcal{L}_Q = -\frac{1}{2} \lambda_{Hh\chi\chi} Hh\chi\chi - \frac{1}{4} \lambda_{HHhh} HHhh - \frac{1}{4} \lambda_{hh\chi\chi} hh\chi\chi - \frac{1}{4} \lambda_{HH\chi\chi} HH\chi\chi. \quad (4.4)$$

where $\beta_g = y_{ttH}/y_{tth}$ is the scale factor with respect to the SM Yukawa top coupling, y_{tth} , and used to tune the effective ggH coupling as β_V is used for VVH couplings. This formalism considers H production through the effective gluon-scalar ggH vertex, which further decays into h with χ . The symmetry of the above Lagrangian follows on the stability of χ . Constraints on coupling constants, masses and other physical quantities follows LHC Run-I compatibility studies [5] on the benchmark scenario where $m_H = 275$ GeV and $m_\chi = 60$ GeV, for analyses of $t\bar{t}H$ production as contained in section 4.

4.3.1 Higgs-boson production in association with a single and a pair of top quarks

The processes informing this study are shown in table 4.1 with the cross sections at leading order (LO) for corresponding benchmark choices. Events are generated using MADGRAPH5. The production of the Higgs boson h and the heavy scalar H

Process	Cross-section (pb)
1 $pp \rightarrow t\bar{t}h$	1.11×10^{-1}
2 $pp \rightarrow t\bar{t}H, H \rightarrow h\chi\chi$	1.48×10^{-2}
3 $pp \rightarrow thj + \bar{t}hj$	2.55×10^{-1}
4 $pp \rightarrow tHj + \bar{t}Hj, H \rightarrow h\chi\chi$	3.90×10^{-2}

Table 4.1: Cross sections (in picobarns) for the mentioned processes as calculated using $m_t = 172$ GeV, $m_h = 125$ GeV, $m_H = 275$ GeV and $m_\chi = 60$ GeV at $\sqrt{s} = 8$ TeV. The renormalisation and factorisation scales for $t\bar{t}h(H)$ are taken to be $\mu_R = \mu_F = m_h(m_H)$, while for $th(H)j + \bar{t}h(H)j$, $\mu_R = \frac{1}{4}\mu_F = (m_t + m_h(m_H))$.

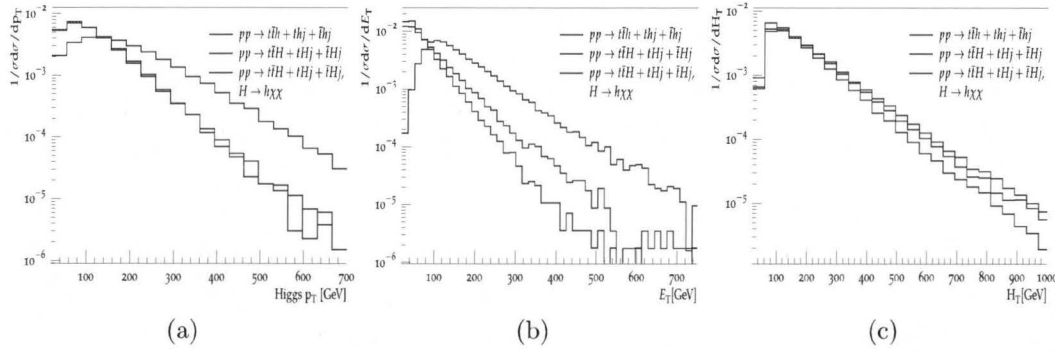


Figure 4.1: Differential distributions of (a) the Higgs transverse momentum (p_T), (b) the missing transverse momentum and (c) H_T as discussed for analysis 1.

with a single top-quark is taken as only being in the 5-flavour (5F) scheme, from the consideration of $2 \rightarrow 3$ processes with b -quark initiation and not in 4F scheme². Studies detailing the schemes and production of the SM Higgs boson in association with single top quark at the LHC, at NLO accuracy in QCD, can be found in work by Demartin [66]. Other studies on Higgs boson production with top pairs beyond NLO [67] have been done with greater accuracy.

According to the SM, the top quark will decay almost exclusively into $W^\pm$ boson and a b quark. The $W^\pm$ boson further decays into a lepton pair ($e\bar{\nu}_e, \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau$) or into quark-jet pair. τ leptons produced by the decay of $W^\pm$ bosons can also decay into leptons ($e\bar{\nu}_e\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau$). For the sake of this analysis, the study is followed in two stages, namely top-quark reconstructions and event selections, through:

- 1 Single lepton channel, and
- 2 Events with same-sign leptons, electrons ($e^\pm$) or muons ($\mu^\pm$) in di-lepton channels.

²The 5F scheme considers b -quark probability distribution functions in proton constituents, whereas in 4F schemes the proton constituents consider four flavours of quarks probability distribution function along with the gluon.

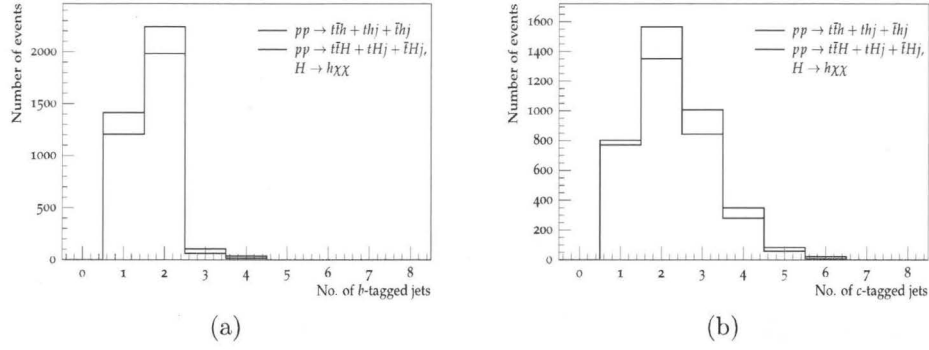


Figure 4.2: Jet multiplicities of b and c -tagged jets, after preselections for the analysis 2.

This is followed through selection of events, cuts on p_T , pseudo-rapidity (η), etc. [68, 69].

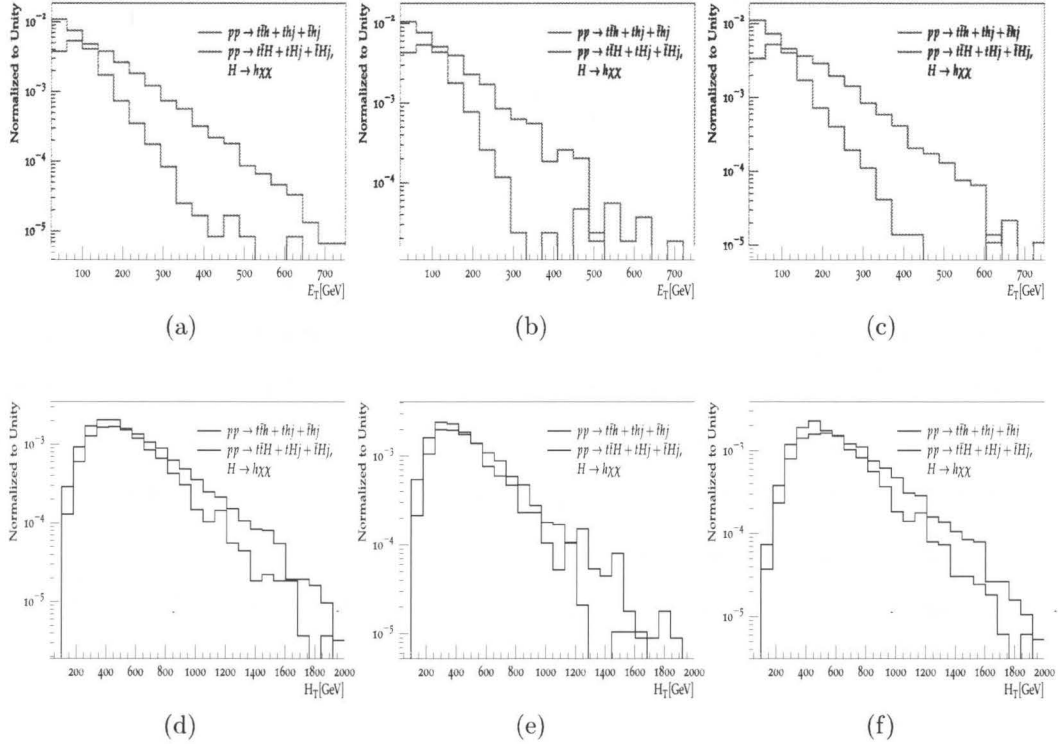


Figure 4.3: Distributions of the missing transverse momentum E_T and scalar sum of jet and lepton transverse momenta H_T after applying the preselection criteria, for events with one, two, or more than two b -tagged jets for analysis 2.

Analysis 1 selects events with jets and leptons having a transverse momentum $p_T > 25$ GeV with pseudo-rapidity $|\eta| < 2.5$ and studies various kinematic distributions. Figure 4.1 shows Higgs p_T , E_T and H_T distributions normalised to the corresponding processes' total production cross sections. The associated Higgs with single top-quark and pair top-quarks processes are added together. In this analy-

sis, save for processes mentioned in table 4.1, an additional process not decaying to H is also studied. The p_T spectrum for h for processes 1-4 and for the H not decayed has different shapes in higher bins (see figure 4.1(a)) owing to $m_H > 2m_h$. Equally, the E_T plot as seen in figure 4.1(b) shows event excesses in higher bins for the decay process $H \rightarrow h\chi\chi$, owing to χ also being a source of missing energy. Figure 4.1(c) shows the H_T distributions defined as scalar sums of the p_T of all jets by $H_T = \sum_j |\vec{p}_T^j|$. Minor difference are seen for the processes relative to the SM.

In the second part of the study, analysis 2, the selections are:

- (1) Selection of 2 leptons with same sign,
- (2) $|\eta| < 2.5$ for leptons,
- (3) p_T cut: leading lepton $p_T > 25$ GeV, sub-leading lepton $p_T > 15$ GeV,
- (4) Number of jets ≥ 2 (at least 2 jets) with $p_T > 25$ GeV within $|\eta| < 3$.

Thereafter special selection cuts are described in Tables 4.2 with number of events for the processes shown in Table 4.1. Different differential distributions corresponding to these analyses are shown in Figs. 4.2 and 4.3. For this analysis we defined H_T as scalar sum of jet and lepton transverse momenta: $H_T = \sum_{j,l} |\vec{p}_T^{j,l}|$. The E_T distributions shows excesses of events for $H \rightarrow h\chi\chi$ in comparison to the SM processes, since χ is the source of missing energy which also discussed in analysis 1. Some excesses in H_T distributions similar to E_T is observed as shown in Figs. 4.3.

Based on table 4.2, processes 13 and 24 are essentially the SM versus $H \rightarrow h\chi\chi$ process. After numerous selections, there are more SM events than those involving the two hypothetical scalars introduced. This analysis shows how a heavy scalar H can be observed in experiments following the decay $H \rightarrow h\chi\chi$ with associated top quarks.

Cut-flows	1	2	3	4	13	24
Total events	30000	30000	30000	30000	60000	60000
2 leptons with same sign	10933	11011	10023	10171	20956	21182
$ \eta < 2.5$ for leptons	9614	9800	7360	7652	16974	17452
p_T cut: leading lepton > 25 GeV, sub-leading lepton > 15 GeV	2305	2622	1156	1326	3461	3948
Number of jets ≥ 2 (at least 2 jets)	2301	2622	1115	1295	3461	3917
exactly 1 b -tagged events	573	661	632	753	1205	1414
≥ 2 b -tagged events	1682	1921	377	462	2059	2383
exactly 1 b -tagged events:						
$400 < H_T < 700$, MET > 40	189	291	116	265	305	556
$H_T \geq 700$, $40 < \text{MET} < 100$	26	22	16	11	42	33
$700 \geq H_T$, MET ≥ 100	36	184	21	58	57	242
at least 2 b -tagged events:						
$400 < H_T < 700$, MET > 40	629	829	102	198	731	1027
$H_T \geq 700$, $40 < \text{MET} < 100$	151	134	19	8	170	142
$700 \geq H_T$, MET ≥ 100	143	643	16	69	159	712
$N_j \in [2,4]$, b -tagged ≥ 1 , $\Delta\phi_{ll} > 2.5$, $H_T > 450$, MET > 40	33	63	32	65	65	128

Table 4.2: Definitions of the different signal regions. N_j is the number of jets that pass the selection requirements, and $\Delta\phi_{ll}$ is the separation in ϕ between the leptons. 13 and 24 is the sum of the processes 1, 3 and 2, 4, respectively.

Chapter 5

Predicting the shape of the dijet mass spectrum in the $Zh + E^T_{miss}$ search

5.1 Introduction

With the discovery of the SM Higgs boson [3, 4] at the LHC, ATLAS and CMS have been investigating the mechanisms governing its interaction with other known particles in the standard model (SM). Initial endeavours by multiple institutions involved compatibility studies with Run-I LHC data at ATLAS and CMS [5], an analysis of multiple models extending beyond standard model (BSM) [5].

A major area of interest and experimental exploration resulting from the discovery of the Higgs boson is the physics related with large E^T_{miss} sector which alludes to the plausibility of new particles that, even though aren't yet a part of SM, are involved in models beyond the standard model (BSM) [70].

To understand the physics that involves large E^T_{miss} , it is important to introduce phenomenological proton-proton (pp) interaction and hadronic collider physics theory. There are two classes of event types in pp collisions, namely minimum bias events and hard scattering events.

Minimum bias events

These are the majority of proton collision events, and are characterized by a small momentum transfer. Sometimes referred to as *soft collisions*, particles from this type of event are scattered at small angles resulting in final-state particles having

large longitudinal momentum and low p_T relative to the beam line of $\langle p_T \rangle \approx 500$ MeV. Almost all the energy from these collisions is dissipated in the longitudinal direction. These are called minimum bias events [71]. Although these events are not for discovery analyses, they are used in a plethora of performance studies for missing transverse momentum reconstruction [72].

Hard scattering events

Complementary hard scattering events are those through which there is a large momentum transfer, and therefore have a high p_T . These momentum transfers allow for the production of massive particles (from high p_T) and final state products at large angles relative to the beam line. Infrequent as these hard scattering events are, they are where the “interesting” physics is. The energy of the partons in both the hard scattering and the minimum bias events is unknown (only the proton energy is known), rendering the missing energy in the final state undefined. The missing energy is, however, reconstructed by momentum conservation law. The transverse momentum of the colliding partons is negligible and so the initial state total momentum is almost entirely longitudinal. In the final states this should also be the case, but the presence of a myriad of causes lead to E_{miss}^T ¹ [72]. These range from, and could be a combination of; particles interacting very weakly (or not at all), particles not produced through the primary collision, detector problems, limited detector acceptance, and many others.

Model dependence

Both CMS and ATLAS have been investigating the properties of the Higgs boson (h) post it’s discovery, encompassing tests on it’s different coupling strengths and spin-CP properties. These tests and global fits indicate that this particle is consistent with the Higgs boson in SM. The presence of excesses and other noteworthy features - including but not limited to the Higgs boson p_T , searches for a di-Higgs boson resonance, the production of the Higgs boson associated with top quarks and VV resonance for vector boson V where $V = Z, W^\pm$, in the data available require more specialized attention. These final states are tested against the hypothesis of a neutral heavy scalar boson H in accordance with the 2HDM [73]. In this investigation, the

¹Missing transverse energy and missing transverse momentum are used interchangeably owing to the generic interchangeable use in literature.

vector in question is $V = Z$.

The production of a charge-parity odd (CP -odd) scalar A is considered, as shown in equation 1.1 as: $pp \rightarrow A \rightarrow ZH \rightarrow l^+l^- b\bar{b} + \chi$. This scalar is produced through gluon fusion from the collision protons and decays into a heavy CP -even neutral scalar H and Z boson. The H decays into a lighter CP -even SM Higgs boson h , which further decays into a bottom quark pair $b\bar{b}$, in association with the dark matter candidate χ - a source of missing energy. The Z decays leptonically by $Z \rightarrow l^+l^-$. The masses of these particles are considered as $m_h = 125$ GeV for the SM Higgs boson, $m_\chi = 60$ GeV for the dark matter (DM) scalar, $2m_h < m_H$ where $m_A > m_H$ for m_A being the mass of the CP -odd scalar A .

5.1.1 The data driven method

The determination of the appropriate signal - and, inadvertently, background - is achieved using data-driven methods using ATLAS simulated data (see section 5.2.1). Background from quantum chromodynamic (QCD) processes such as hadronic jets and that from electro-weak (EW) processes such as W + jets, Z + jets and $t\bar{t}$ is suppressed. The prediction of this background is crucial in the $Zh + E_{miss}^T$. This is done by discriminating events (see section 5.2.3) from processes outside the signal particle(s) production and is the data-driven method. The discrimination criteria involves quantities such as (a) the number of jets with a minimum p_T threshold, (b) the determination of jet tagging efficiencies, (c) the determination of flavour similarity (or the opposite flavour) in leptonic searches, (d) the invariant mass distribution in some mass window and (e) considerably large E_{miss}^T (relative to the beam line as seen in section 5.1). The complete list and order of application of the discrimination shall be discussed in section 5.2.3.

5.2 $Zh + E_{miss}^T$ search

The objective of this analysis is to compare flavour schemes for the decay of the Z boson into leptons (electrons and muons) as described by the signal, using a data driven method. The suppression of this background allows the prediction of the data driven method employs the proton collisions giving rise to the signal. The decrease rate of the number of background events is expected to be greater than that of the main signal which result in better signal to noise ratio.

5.2.1 Data and event simulation

The data used in this analysis were recorded with the ATLAS detector during the 2015 and 2016 pp collision runs at $\sqrt{s} = 13$ TeV and correspond to a total integrated luminosity of 3.32 fb^{-1} . The data are required to satisfy a number of criteria that ensure that the ATLAS detector was in good operating condition while the data were recorded. A number of Monte Carlo simulation samples are used to model background and signal processes for this search, in addition to the data.

The simulated events for the production processes $A \rightarrow ZH$ are generated with MADGRAPH5_AMC@NLO 2.2.2 [74] [75] for gluon fusion and NNPDF2.3LO [76] parton distribution functions (PDFs). Hadronization and parton showering are performed with PYTHIA8.186 [77] for all signal events simulated. The masses of the involved particles are fixed to those of the SM, plus $m_h = 125 \text{ GeV}$ and $m_\chi = 60 \text{ GeV}$. However, the branching fraction for the $h \rightarrow b\bar{b}$ process is $58 \pm 2\%$ [78], which is a function of the model parameters. The mass of boson A is fixed and the narrow-width approximation used in the simulation, although its width is allowed to deviate from the narrow-width by 2HDM.

The background process kinematics and the normalization of SM background are simulated using Monte Carlo (MC) samples. Two significant background, $W + \text{jets}$ and $Z + \text{jets}$, are simulated with SHERPA 2.1.1 [79] using CT10 PDFs [80] with parton shower tuning by Sherpa authors. The pair of top quarks $t\bar{t}$ is simulated using POWHEG [81,82] with the POWHEG-BOX framework [83] and using the same CT10 PDFs in association with a PYTHIA 6.428 interfacing [84]. The top quark mass is taken at 172.5 GeV and constrains the mass of the heavy scalar H . The $W/Z + \text{jets}$ cross sections are calculated at Next-to-Next-to-Leading Order (NNLO) accuracy and the top quark pair is calculated to Next-to-Next-to-Leading Log (NNLL) accuracy. Production of the single top is simulated with POWHEG using the CT10 PDFs in association with the PYTHIA 6.428 interfacing using the CTEQ6L1 PDFs for the parton shower and NLO QCD cross section calculations using HATHOR v2.1 [85,86]. WW , WZ and ZZ , also termed diboson background, are simulated with SHERPA 2.1.1 using CT10 PDFs and NLO normalization cross section [87]. The simulation for the production of the SM Higgs boson h in association with W/Z boson employs the use of PYTHIA8.186 [77] for products induced by quarks, and POWHEG show-

ered with PYTHIA8.186 for the production of Z and H induced by gluons. The use of CT10 PDFs is employed in both quark and gluon-induced production. The ZH process is normalized to NNLO+NLO(EW) cross sections [78] and, for this search, the production of the Higgs boson is considered as background.

5.2.2 Object definition and reconstruction

The explicit reconstruction of many-particle vertices and their corresponding particles, the kinematic properties of electrons, muons, τ leptons, jets and missing transverse momentum are crucial in this analysis. This section describes the reconstruction of these objects.

The reconstruction of electrons is done through matching energy clusters in the electromagnetic calorimeter, using an ATLAS algorithm (sliding window algorithm) which clusters calorimeter cells within fixed-sized volumes [88]. These electrons are to satisfy electromagnetic shower shape, track quality and track cluster matching criteria. These requirements are applied on a likelihood-based criteria with the terms “Loose”, “Medium” and “Tight” used to denote different working points as ranked according to increasing purity [89]. Muon identification is achieved through matching tracks located in the inner detector, as shown in section 2.2.3, to either complete tracks or segments of tracks reconstructed in the muon spectrometer [90]. Muons, like the electrons, subscribe to quality criteria from the inner detector and muon spectrometer track. These particles are required to have a minimum p_T of 7 GeV and pseudo-rapidity $|\eta| < 2.7$ and $|\eta| < 2.47$ for the muons and electrons, respectively, corresponding to lying within a region that allows for good reconstruction and identification. Lepton candidates are required to pass the “Loose” criteria. They are also isolated by enforcing selection criteria on the sum p_T of tracks located in a cone around the direction of the leptons with the size thereof being a function of the lepton p_T .

5.2.3 Analysis strategy and event selection

The signal of interest for this analysis is the gluon fusion production and decay of the CP -odd scalar by the $A \rightarrow ZH \rightarrow l^+ l^- b \bar{b} \chi \chi$ mode of decay, where $l^\pm = e^\pm, \mu^\pm$. This signal is optimised, primarily, by selecting events on the basis of the number of leptons, the transverse momentum of the particles at large and the number of

b -tagged jets. For the number of leptons (two in this analysis), topological and kinematic discriminants inflate the search sensitivity [91].

The analysis is started by optimising the signal sample in relation to relevant sources of background. These sources are $W + \text{jets}$, $Z + \text{jets}$, diboson combinations of W and Z , a single top quark t and $t\bar{t}$. The normalization of these background cross-sections is done using ATLAS framework available yield samples, according to the ATLAS framework used for Vh analysis [91, 92].

The $Zh + E_{miss}^T$ analysis employs the software framework of the Vh analysis, and uses the 2-lepton channel. In this channel, events are recorded using a combination of single-lepton triggers at un-prescaled values. The p_T energy threshold is 24 GeV for isolated electrons and 20 GeV for isolated muons. The first selection criteria, known as the lepton trigger, discriminates against events with leptons that do not match some offline-reconstructed lepton in the events [93].

For signal optimisation, the three main selection criteria have been identified as:

- 1 Same flavour and opposite sign leptons,
- 2 At least two central jets with b -tagging, and
- 3 The identification of exactly one and at least two b -tagged jets. In the case of at least two b -tagged jets, the leading jet (the jet with the greatest p_T) must have $p_T > 45$ GeV.

Other requirements are as follows:

- i The leptons are to have a transverse energy $p_T > 25$ GeV,
- ii The invariant mass of the leptons $m_Z(m_{ll}) \in [65, 115]$ GeV,
- iii $E_{miss}^T > 100$ GeV and
- iv The azimuthal angle separation within leading (sub-leading) jets ordered by p_T with P_{miss}^T should be $\Delta\phi_{j_{1(2)}E_{miss}^T} > 0.5$.

5.2.4 Signal and background

The signal channel studied in this analysis has contamination from multiple background processes, notably $Z + \text{jets}$ and $t\bar{t}$ events as described in section 5.1.1. In

the $Zh + E_{miss}^T$ analysis case, these backgrounds prevail as a result of the decay of Z by $Z \rightarrow l^+l^-$. Single-top and diboson production also contribute, at some small percentage, to the presence of background, together with non-resonant $h \rightarrow b\bar{b}$ production.

The $W/Z + \text{jets}$ simulated samples are categorized in accordance with the true flavour of the two small- R jets resulting from the $h \rightarrow b\bar{b}$ in the region of low Z p_T , and the true flavour of the two leading track-jets associated with the leading large- R jet in the high Z p_T region. The flavour of the true jet is ascertained using a $\Delta R < 0.3$ match between the jets and hadrons (either b or c) with $p_T > 5$ GeV. If either of these simulated hadrons are found to be associated with the jets as reconstructed, they (the jets) are labelled as true. If not, as in neither b - nor c -hadrons are associated with the reconstructed jet, they (the jets) are labelled as a true light jet. The latter shall be initiated by either of the three quarks u , d or s , or by a gluon. These samples are then further split into six groups by virtue of the following association schemes: $W/Z + bb$, $W/Z + bc$, $W/Z + bl$, $W/Z + cc$, $W/Z + cl$ and $W/Z + ll$. The $Z + \text{jets}$ backgrounds are the combination of all three permutations of Z with b and c , while the $W + \text{jets}$ backgrounds are the union of $W + bb/bc/cc/ll$.

The enhancement of specific backgrounds, achieved by inverting selection criteria for the creation of independent data and Monte Carlo (MC) regions (these regions are referred to as “Control regions” or CRs), are used to improve signal region (SR) background process description.

The $Z + \text{jets}$ background study employs the use of a set of $W/Z + \text{jets}$ CRs as defined by the inversion of the selection criteria on dijet (jet) masses m_{dijet} (m_{jet}) in the low Z p_T (high Z p_T) category. The definition of two sub-regions in this CR is a result of requiring that either two jets are b -tagged, or that only one is. In the low Z p_T channel, there are two additional CRs of enriched $t\bar{t}$ (one for the case of 1 b -tag and the other for the 2-tag case) defined by the requirement that the two charged leptons be of different lepton flavours and have mass $m_{e\mu} > 40$ GeV.

5.2.5 Systematic uncertainties

Systematic uncertainties regarded as relevant, such as those regarding the trigger selection, object reconstruction and identification, object energy, momentum, mass calibrations and resolutions, are considered. From these, the uncertainties regarded as most important are those associated with the calibration and resolution of the

small- R and large- R jet energy, the calibration and resolution of the large- R jet mass in the case of the high Z p_T category, and the determination of the jet b -tagging efficiency and rate of mistagging, as done in the reference [94], reference [95] and reference [96–98] respectively. The evaluation of the mentioned uncertainties, although interesting and involved studies on their own, are of marginal importance in this study and shall not be further investigated.

Other sources of background, outside $Z + \text{jets}$ and $t\bar{t}$, having normalisations predicted theoretically, and bearing in mind the integrated luminosity uncertainty of 5%, have the assigned uncertainties 26% for $Z + l$, 30% for $W + bb/bc/cc/bl$, 30% for $W + cl$, and 10% for $W + l$, taking into account the uncertainty on the inclusive $W/Z + \text{jets}$ cross section [99] and on the experimental acceptance from comparing nominal SHERPA 2.1.1 generated $W/Z + \text{jets}$ samples with those from alternative simulators using factorisation, renormalisation and resummation scales of either a half of double the Sherpa scale. Furthermore, 4% for single-top in the s-channel and t-channel, 7% for single-top in the Wt -channel [85, 86], and 50% for the associated $W/Z + h$ production [100, 101] were also assigned to the luminosity uncertainty. Additionally, a further 13% (35%) on the uncertainty of the relative normalisation of $Z + cl$ to $Z + bl$ ($W + bl$ to $W + bb$) has been added from comparing SHERPA 2.1.1 samples.

Uncertainties in the order of 30% on the relative normalization of the high and low Z p_T regions between 9% and 17% in the relative normalisation range of the lepton decay channel have been estimated for each source of background by comparing SHERPA 2.1.1 and MADGRAPH5_AMC@NLO 2.2.2 at leading order to a PYTHIA 8.186 interface for $W/Z + \text{jets}$ backgrounds. The uncertainties on the masses and transverse masses of the Z and h combined mass m_{Zh} and m^T_{Zh} (and, by extension, m_{ZH} and m^T_{ZH}), respectively, for the $W/Z + \text{jets}$ distributions are determined by comparing predictions from SHERPA 2.1.1 and MADGRAPH5_AMC@NLO 2.2.2. In the $t\bar{t}$ background case, a 30% uncertainty on the relative normalization of the high and low Z p_T regions between 2.5% and 10% in the relative normalisation range of the signal and control regions have been estimated by comparing POWHEG and MADGRAPH5_AMC@NLO 2.2.2 with those produced with the factorisation and renormalisation scale either doubled or halved. The comparison is also used for the estimation of the uncertainties on shape of the mass distributions m_{Zh} and m^T_{Zh} (and, by extension, m_{ZH} and m^T_{ZH}) for the $t\bar{t}$ events.

The uncertainty on the cross section for the signal process $A \rightarrow Zh$, and by extension on $A \rightarrow ZH$, for the mass $m_A = 600$ GeV, after some internal² likelihood fit to the data, is primarily a result of the limited number of events in data - this is responsible for close to 80% of the total uncertainty when related to that from limited MC simulated events, modelling systematics and uncertainties from experiment which all contribute the remainder of just over 20%.

5.2.6 Results

The signal optimisation as explained in section 5.2.3 is achieved by suppressing background via implementing cuts on observed quantities such as energy, mass, trajectory, etc. After the background and signal event samples are simulated (see section 5.2.1) for $\sqrt{s} = 13$ TeV and integrated luminosity 3.32 fb^{-1} , the decreasing number of events due to the selection of events satisfying that cut is shown for each cut. Tables 5.1 and 5.2 show the number of events after each cut and, subsequently, the suppression of the background. Note the severe decrease in the number of $Z + \text{jets}$ events resulting from the cuts. Thereafter, the distributions of the quantities of interest - the E_{miss}^T , the dijet mass (m_{jj}) and the jet signal frequency (njet) - for the 1 and 2 b -tag cuts under the same and different flavour schemes are provided. From the distributions provided, the ratio of the number of events between the two flavour schemes for the quantities of interest is shown.

Background suppression

Tables 5.1 and 5.2 show the suppression of the number of events after each cut. For the diboson samples (the combined background of ZZ , WZ and WW) in both flavour schemes, the number of events is zero after enforcing the cut on the number of b -jets. The number of $Z + \text{jets}$ samples is also zero for the b -jet p_T cut in the different flavour scheme. For samples bearing no events, statistical analyses are not possible.

Table 5.1: Shown are the number of weighted events for each cut in the same flavour scheme over background samples

²Internal papers, plots, etc. are for the use of ATLAS members

$ee/\mu\mu$	Single-top	Diboson	W +jets	Z +jets	$t\bar{t}$
No Cuts	9790.13 $\pm$ 16.85	6579.72 $\pm$ 75.22	43970.93 $\pm$ 660.50	1883642.25 $\pm$ 4824.70	107052.43 $\pm$ 99.49
Opposite Charge	8588.12 $\pm$ 15.70	6366.03 $\pm$ 74.13	24653.45 $\pm$ 478.14	1861689.12 $\pm$ 4804.25	99578.14 $\pm$ 95.95
Same Flavour	4309.85 $\pm$ 11.12	6166.61 $\pm$ 72.80	11658.15 $\pm$ 323.77	1843588.00 $\pm$ 4791.81	49938.71 $\pm$ 67.96
Lepton p_T	2413.90 $\pm$ 8.27	4344.61 $\pm$ 61.08	890.54 $\pm$ 84.10	1347672.12 $\pm$ 4340.26	29059.95 $\pm$ 51.84
m_{ll}	639.91 $\pm$ 4.26	4191.63 $\pm$ 60.12	182.57 $\pm$ 45.40	1281533.62 $\pm$ 4287.27	8188.96 $\pm$ 27.53
At least 2 jets	435.30 $\pm$ 3.51	3422.53 $\pm$ 54.76	130.24 $\pm$ 32.40	500706.16 $\pm$ 2484.59	7443.30 $\pm$ 26.24
$E_{miss}^T > 100$ GeV	89.15 $\pm$ 1.59	11.19 $\pm$ 2.39	12.57 $\pm$ 4.17	706.34 $\pm$ 55.94	1571.01 $\pm$ 12.04
$\Delta\phi(j1, E_{miss}^T) > 0.5$	87.76 $\pm$ 1.58	9.28 $\pm$ 1.76	12.45 $\pm$ 4.16	570.42 $\pm$ 52.97	1541.29 $\pm$ 11.93
$\Delta\phi(j2, E_{miss}^T) > 0.5$	79.67 $\pm$ 1.50	3.40 $\pm$ 0.98	12.14 $\pm$ 4.16	447.34 $\pm$ 49.35	1368.99 $\pm$ 11.24
Exactly 1 b -jet	42.97 $\pm$ 1.10	1.06 $\pm$ 0.62	0.46 $\pm$ 0.27	24.93 $\pm$ 4.20	649.61 $\pm$ 7.75
Exactly 2 b -jets	16.11 $\pm$ 0.68	0.00 $\pm$ 0.00	0.04 $\pm$ 0.02	2.37 $\pm$ 1.18	490.09 $\pm$ 6.72
b -jet $p_T > 45$ GeV	15.04 $\pm$ 0.65	0.00 $\pm$ 0.00	0.03 $\pm$ 0.02	1.56 $\pm$ 0.96	462.16 $\pm$ 6.53

Table 5.2: Shown are the number of weighted events for each cut in the different flavour scheme over background samples

$e\mu/\mu e$	Single-top	Diboson	W +jets	Z +jets	$t\bar{t}$
No Cuts	9790.13 $\pm$ 16.85	6579.72 $\pm$ 75.22	43970.93 $\pm$ 660.50	1883642.25 $\pm$ 4824.70	107052.43 $\pm$ 99.49
Opposite Charge	8588.12 $\pm$ 15.70	6366.03 $\pm$ 74.13	24653.45 $\pm$ 478.14	1861689.12 $\pm$ 4804.25	99578.14 $\pm$ 95.95
Different Flavour	4278.26 $\pm$ 11.08	199.42 $\pm$ 13.98	12995.30 $\pm$ 351.84	18101.14 $\pm$ 345.59	49639.43 $\pm$ 67.74
Lepton $p_T > 25$ GeV	2387.51 $\pm$ 8.22	41.22 $\pm$ 6.79	1086.84 $\pm$ 107.67	7299.90 $\pm$ 225.93	28852.22 $\pm$ 51.65
m_{ll}	638.78 $\pm$ 4.26	13.41 $\pm$ 3.57	247.19 $\pm$ 56.10	5688.96 $\pm$ 206.32	8119.21 $\pm$ 27.40
At Least 2 jets	438.17 $\pm$ 3.53	8.56 $\pm$ 3.10	189.05 $\pm$ 46.39	2288.16 $\pm$ 124.05	7368.57 $\pm$ 26.10
$E_{miss}^T > 100$ GeV	88.70 $\pm$ 1.59	1.40 $\pm$ 0.74	8.03 $\pm$ 4.06	38.19 $\pm$ 9.94	1569.08 $\pm$ 12.04
$\Delta\phi(j1, E_{miss}^T) > 0.5$	87.11 $\pm$ 1.57	0.77 $\pm$ 0.47	7.99 $\pm$ 4.06	16.28 $\pm$ 8.26	1542.07 $\pm$ 11.93
$\Delta\phi(j2, E_{miss}^T) > 0.5$	78.80 $\pm$ 1.49	0.36 $\pm$ 0.24	7.52 $\pm$ 4.05	7.40 $\pm$ 6.29	1364.80 $\pm$ 11.22
Exactly 1 b -jet	43.44 $\pm$ 1.11	0.19 $\pm$ 0.18	0.67 $\pm$ 0.27	1.29 $\pm$ 0.57	657.72 $\pm$ 7.79
Exactly 2 b -jets	16.23 $\pm$ 0.68	0.00 $\pm$ 0.00	0.02 $\pm$ 0.02	0.06 $\pm$ 0.11	480.07 $\pm$ 6.65
b -jet $p_T > 45$ GeV	15.23 $\pm$ 0.66	0.00 $\pm$ 0.00	0.02 $\pm$ 0.02	0.00 $\pm$ 0.00	449.80 $\pm$ 6.44

Observable distribution plots

Presented in this part of the results section are (a) the E_{miss}^T , (b) the dijet mass (m_{jj}) and (c) the jet signal frequency (njet) for the 1 b -tag cut under the same flavour and different flavour schemes. The distributions are shown on a logarithmic scale³.

As quick checks for the validity of the plots, note the order of precedence for the cut-flow tables' cuts. The missing transverse energy represent the E_{miss}^T for one and two jets correspond to the selection after the 100 GeV cut, and their plots have a lower bound of 100 GeV. The jet signal plots showing the event distributions

³the logarithmic (or log scale) is a type of non-linear scale commonly used in high energy physics for representing data on a wide range.

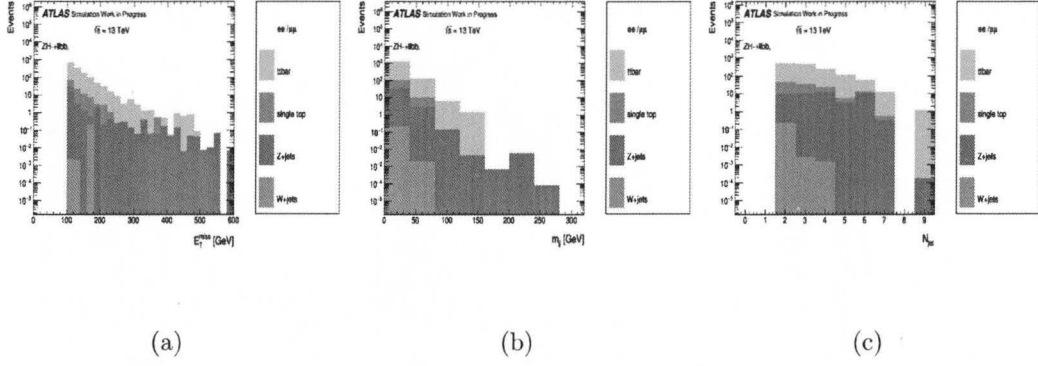


Figure 5.1: Distributions of (a) the E^T_{miss} , (b) the dijet mass (m_{jj}) and (c) the jet signal frequency (n_{jet}) for the 1 b -tag cut under the same flavour scheme

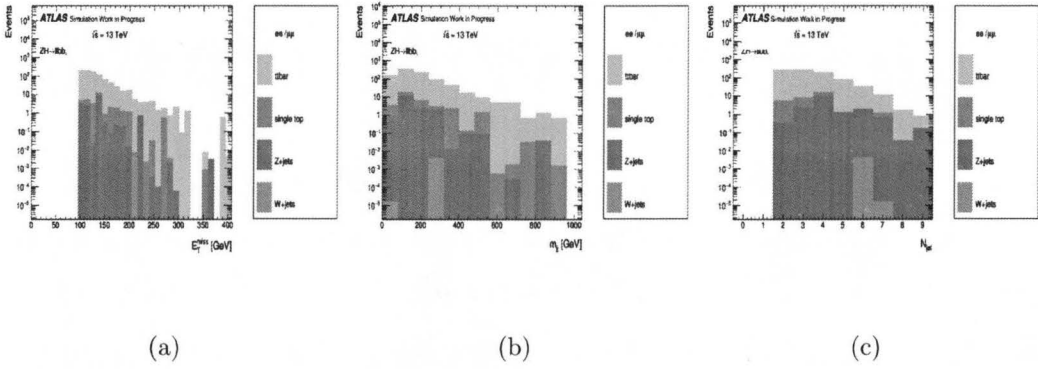


Figure 5.2: Distributions of (a) the E^T_{miss} , (b) the dijet mass (m_{jj}) and (c) the jet signal frequency (n_{jet}) for the 2 b -tag cut under the same flavour scheme

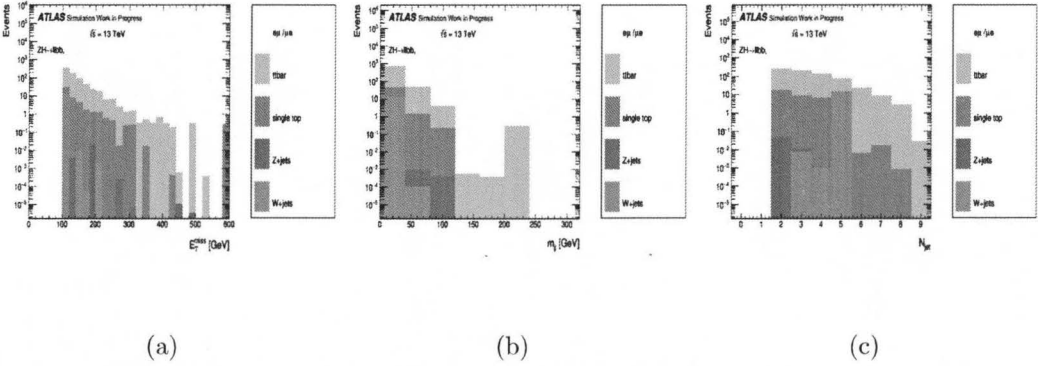


Figure 5.3: Distributions of (a) the E^T_{miss} , (b) the dijet mass (m_{jj}) and (c) the jet signal frequency (n_{jet}) for the 1 b -tag cut under the different flavour scheme

for each number of jets at one and two jets have a lower inclusive bound of 2 jets, corresponding to their order in the cut-flow. These distributions, in totality, show how many events correspond to each quantity. To answer the question of dijet mass distribution prediction, however, the ratio between the same flavour scheme and the different flavour scheme should be low relative to some acceptable value. The comparison is achieved, first by data-driven background suppression as done above,

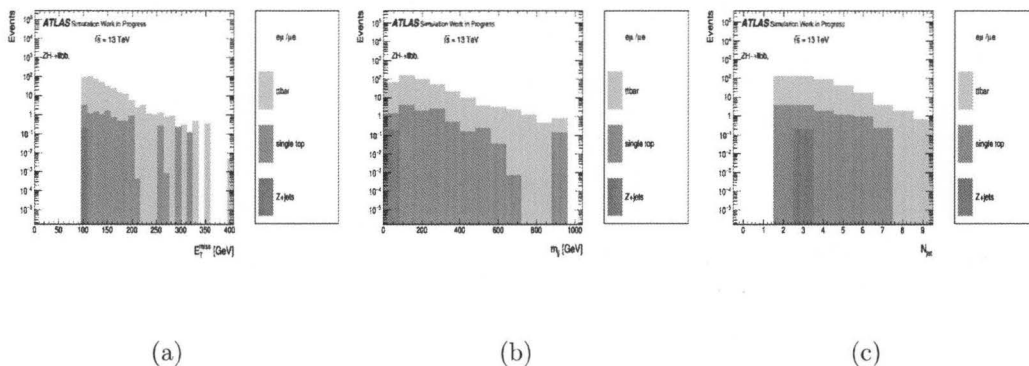


Figure 5.4: Distributions of (a) the E_T^{miss} , (b) the dijet mass (m_{jj}) and (c) the jet signal frequency (n_{jet}) for the 2 b -tag cut under the different flavour scheme

and by ratio comparison as done below in section 5.2.6.

Ratio plots

The ratio of the same-flavour and different-flavour decay schemes is calculated by $(x_{diff} - x_{same})/x_{same}$, and represents how far the two values are from each other for a given mass or energy. Figure 5.5 shows the superimposed normalized number of events for the dijet (inferred) mass of the same- and different-flavour decays, and the ratio between them as explained above.

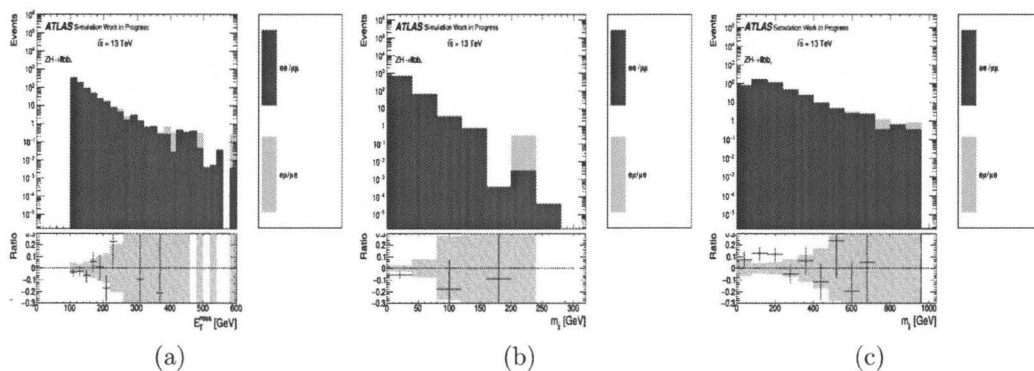


Figure 5.5: The differential distributions of (a) the E_T^{miss} , (b) the dijet mass distribution (m_{jj}) for exactly 1 b -jet, and (c) the dijet mass distribution (m_{jj}) for exactly 2 b -jets.

5.3 Discussion

In this section, the formalism for the dijet mass prediction was constructed. The computational aspect of the data taking process, the events of interest in the study, the models informing our analysis of said study, and the break-down of the data-

driven method were discussed in section 5.1.

Next, a precursory investigation of the production of a heavy scalar boson H in association with a top and anti-top quark was used to explain the excesses in the Higgs boson decay scheme as presented in section 4. These excesses were attributed to the χ dark matter candidates as a possible source of missing energy. This part was vital in the appreciation of the heavy scalar H as an extension to the 2HDM, and show the effective Lagrangian of a theory based on the 2HDM with additional dark matter candidate χ .

Following the theoretical rigour involved in building a model, the data and event simulation were introduced. The signal and background were defined in line with the processes of interest investigated in the study. The analysis strategy, selection of events and reasoning thereof, and systematic uncertainties intrinsic in the analysis framework are discussed from section 5.2. This analysis begins to converge in section 5.2.6 when the cuts shown in tables 5.1 and 5.2 reduce the number of background events. The distribution of the number of events for physical quantities such as E_{miss}^T or lepton masses, not pinned against actual data, were shown for each cut where statistics are available (where there is a non-zero quantity).

The question posed in the analysis chapter of this dissertation, that of using a data-driven method in predicting the shape of the dijet mass distribution of the $Zh + E_{miss}^T$ analysis, starts being answered by the ratio plots shown in figure 5.5.

Chapter 6

Conclusions

The objectives of this dissertation are to determine the effects of neutron induced radiation damage on the optical properties of plastic scintillator UPS 923A and to study the data driven method, employed for predicting the dijet mass spectrum in the $Zh + E_{miss}^T$ analysis.

The former objective is executed by first understanding the kinds of processes present in the interactions between the base material of the scintillator and ionizing particle radiation. These interactions are characterized by their effects on the optical properties of the base material and, subsequently, the scintillator. These effects, termed radiation damage as they alter the detecting properties of the scintillator and arise from ionising radiation, are studied by irradiating identical scintillator samples at varying doses. The transmittance, luminescence and light yield of the samples is tested as a function of radiation dose.

The latter objective, that of studying the data driven method in the dijet mass distribution prediction, is realised by first investigating prior work on the production of the standard model Higgs boson and the heavy scalar boson H . Once the production modes of the Higgs are established, simulation of the signal is described and the distributions and tables pertaining to those processes are given.

From the experiment performed on the optical properties of plastic scintillator UPS 923A, the complexities in characterising and formulating radiation damage were realised. The changes in the transparency and light yield of the scintillator samples, although proportional to the radiation doses the samples were exposed to, serve mostly as evidence for the influence of radiation damage and more experimentation is required in more completely formulating the chemical and structural changes to

the material resulting in these changes. For transmittance studies, modelling the steric orientation of the plastic for more general cases, involving the scintillator additives and the more complete geometries of the samples, would allude to more specific causes of the optical property changes. Existing work, as done for toy models of plastic-like structures in electron paramagnetic resonance studies [31], would serve as a guide for exploring this work. The luminescence, inconclusive as the results from the experiment were, did “shed light” onto an important component of optical experimentation, that of the material’s interaction with EMR. Be that as it may, manipulating the averaging of the eyepiece would increase the effective surface area probed by the laser. This could, at least for the same reasons the experiment was inconclusive, show more results because of more statistics.

Predicting the dijet mass spectrum shape, even though not the crux of this analysis experiment, was a core part of it. The main area of interest was, as done in this experiment, validating the data driven method. For that, the data driven method had to be defined in the context of high energy physics analysis. This was done by formalising the models that are tested out, the kind of processes that occur under the assumptions and theories posed by these models, a translation of these theories into a computational regime, and the eventual manipulation of the quantities involved in these models. At this point, dark matter and other particles not part of the standard model were introduced and incorporated into the analytical rigour of quantitative analysis. Once the framework was established, the decay of the CP-odd scalar A was analysed by virtue of limiting background events. At this point does the data driven method become apparent. The results from the number of events were compared for different flavour schemes, and the results, seen on figure 5.5, show how close one flavour scheme is to the other.

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Appendix A

Radiation damage in plastic scintillators

A.1 Physics

Orbital States

Section 3.3 mentions the singlet and triplet state. The singlet state corresponds to electrons with paired spin in the molecule and the triplet state corresponds to the set of unpaired electrons. The electrons' probability of occupying either spin states depends on the orbital energy of the valence electrons and the electrostatic exchange strengths between electrons exhibiting parallel spin in the ground state [102], and the transitions between each state are induced by energy absorption of specific frequencies.

Dosage

Section 3.3 alludes to ionizing radiation dosage. There are three types of quantities used to measure absorbed dose from radiation. Fluence is the number of particles or photons or the quantity of energy passing through a given unit area of a material. Kerma is the energy quantity transferred from the incident uncharged particles to charged particles within the target medium. The final measure is the energy transfer rate from charged particles within the medium to the medium itself, known as stopping power which leads to absorbed dose. These tend to be used interchangeably with some infinitesimal conversion in between as observed from the following

relations:

$$\Phi = \frac{dN}{da}, \Psi = \frac{dE}{da}, D = \frac{d\bar{\epsilon}}{dm} \quad (\text{A.1})$$

As observed in relation A.1, Φ represents the number of particles dN incident on a surface of area da and is measured in m^{-2} , Ψ represents the energy dE incident on a surface area and is measured in Jm^{-2} , and absorbed dose D is defined as the mean energy $d\bar{\epsilon}$ imparted onto matter of mass dm [103]. For a target material of known mass and volume (hence density), and a known number of incident particles of a specified energy, one can move from these quantities quite simply.

Radiation measure units

In nuclear physics, a number of quantities and relations are vital in expressing both nuclear and particle interactions. A notable relation as seen in section 3.3.3 is the *rad* or the absorbed radiation dose defined as:

$$1 \text{ rad} = 0.01 \text{ Gy} = 0.01 \text{ J}\cdot\text{kg}^{-1} = 6.24\cdot 10^{18} \text{ eV/kg} \quad (\text{A.2})$$

where Gy is the symbol for *gray*.

Stopping power

The term *stopping power* $-dE/dx$ refers to the average energy lost per unit length in a target material. It is a function of the incident particles' momentum and is expressed by relation A.3 known as the Bethe-Bloch equation [104].

$$-\frac{dE}{dx} = \frac{Kz^2Z}{A\beta^2} \left[\frac{1}{2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 E_{max}}{I^2}\right) - \beta^2 - \frac{1}{2} \delta(\beta\gamma) - \frac{C}{Z} \right] \quad (\text{A.3})$$

The Bethe-Bloch equation only holds for materials made of pure elements. It is also worth noting that the incident particles' energy loss decreases with an increase in their energy, at velocities higher than those of the electrons within the atom. At energies lower than the atomic electrons', the incident particles energy losses are increased with an increase in their energy. A maximum energy loss is reached when the incident particles and the atomic electrons are comparable in energy.

Plastic Scintillator UPS 923A samples

Three of the four polystyrene-based plastic scintillator UPS 923A samples as seen in figure A.1 were irradiated at varying neutron fluences.

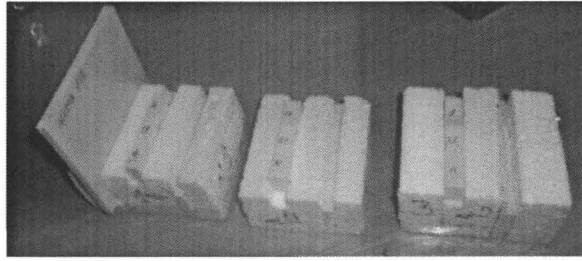


Figure A.1: The three of four plastic scintillator UPS 923A samples before irradiation.

Light yield experimental setup

The setup of the electronic for the light yield experiment are shown in figure A.2 below. Each image in the figure shows an additional connection in the setup, as many of the connections cross-connect.

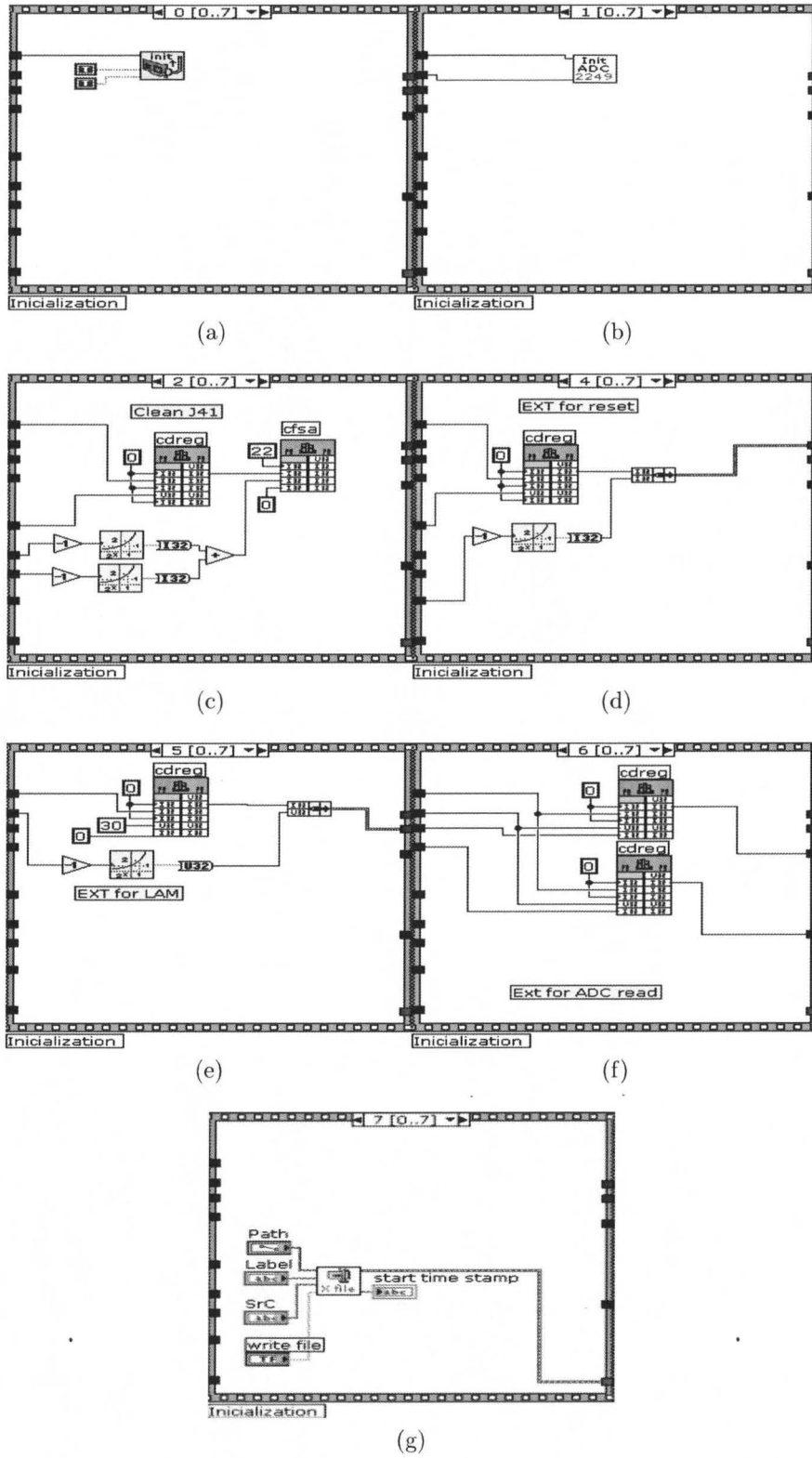


Figure A.2: Electronics for the light yield experiment setup

