

Searching for Supersymmetry using the Higgs Boson

Inauguraldissertation

der philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Thomas Weston

aus dem Vereinigten Königreich

Leiter der Arbeit:

Prof. Dr. Michele Weber

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Der Dekan

Prof. Dr. Zoltán Balogh

Abstract

The Large Hadron Collider and its experiments constitute the largest particle physics research programme to date, allowing for extensive research of the existing Standard Model and for potential evidence of physics beyond that of our current comprehension. This thesis documents a search for new physics and development towards future silicon pixel detectors for the envisioned upgrade to the ATLAS pixel detector in accordance with the High Luminosity-LHC project. Supersymmetry represents a well motivated extension to the existing Standard Model that could provide solutions to some of its most significant and unresolved problems. This thesis presents the search for the supersymmetric partner to the bottom-quark, the bottom-squark ($\tilde{b}_1$), using the full ATLAS Run 2 dataset. Following from its recent discovery, the Higgs boson is utilised as a tool in order to search for new physics in complex decay chains involving other supersymmetric particles known as neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0$). Given the dominant decay of the Higgs boson into a pair of b -quarks, the search targets final states with up to six hadronic deposits identified to have originated from b -quark fragmentation and large missing transverse momentum, posing an unlikely final state to have arisen from known Standard Model processes. In the absence of a significant deviation from the Standard Model expectation, limits on both generic models of new physics and on the signal models in question are derived. Exclusion limits at the 95% confidence level are placed on the visible cross-section and on the mass of the bottom-squark for various assumptions about the mass hierarchy of the $\tilde{b}_1, \tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. Bottom-squark masses up to 1.5 TeV are excluded for models with fixed $m(\tilde{\chi}_1^0) = 60$ GeV and $\tilde{\chi}_2^0$ masses $\in [0.5, 1.1]$ TeV. In the case of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario, bottom-squark masses up to 1.3 TeV are excluded for $\tilde{\chi}_2^0$ masses up to 750 GeV. As the first search for such scenarios carried out by ATLAS in Run 2, these results represent a considerable increase to the previous constraints on bottom-squark production. The comparatively lower fluence expected at the outer layers of the upgraded pixel detector during HL-LHC represents an opportunity to instrument the detector with a promising candidate technology. The HV-CMOS technology is a novel pixel detector concept that allows the pixel sensor and readout chip to be implemented in the same silicon bulk, allowing for significant reduction in cost of production. Prototype devices fabricated in different feature-sizes and resistivities were characterised after irradiation through extensive beam test measurements. The devices proved to be highly efficient at over 99% for all devices and with excellent timing properties. These promising results represent an initial step towards the development of fully monolithic HV-CMOS pixel detectors.

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Introduction

Particle physics addresses the most fundamental of questions concerning nature and our reality: *what is matter made from?* It strives to discover the laws by which our universe abides and reveal the elementary constituents from which it is built. Since the turn of the twentieth century, the interplay between theoretical and experimental particle physics has been of crucial importance to the development of the field. Just as theoretical predictions have challenged the creativity and guile of experimentalists to construct machines capable of providing affirming or repudiating evidence, unexpected experimental observations have challenged theorists to construct mathematical descriptions that explain the observed phenomena. Together, these profound theoretical concepts and experimental observations construct what is referred to as the Standard Model (SM). The SM of particle physics epitomises our current understanding of the fundamental particles and the forces which allow them to interact. The SM provides a remarkably accurate framework of the currently understood phenomena in our universe, encapsulating its complexity into just two types of particles: fermions and bosons.

Though considered a modern triumph of physics, the SM does not explain all that we observe in nature. Despite the vast content of the SM, it describes but a fraction of the content of the universe and provides no particle candidate for the unknown dark matter and dark energy, representing a significant proportion of the universe. Perhaps more intriguingly, it is unknown why there exists an asymmetry between the matter and anti-matter. This is to say, *why are we even here at all?*

Substantial effort is made to investigate Beyond the SM (BSM) physics, seeking to provide potential extensions to the existing framework. A significant physics research programme at CERN (European Organisation for Nuclear Research) is underway, with many experiments based at the Large Hadron Collider (LHC) attempting to confirm or refute the existence of supersymmetry amongst other BSM theories. In December 2018, the second successful data taking period of the LHC concluded, whereby it was shut down for planned upgrades and improvements. Run 2 saw an increase in the operational centre-of-mass energy, rising from 8 TeV to 13 TeV, allowing the searches for particles originating from BSM physics to push their discovery sensitivities, producing unprecedented mass exclusion limits.

Amongst the many BSM theories intending to provide extensions to the existing SM framework, one of the more notable is supersymmetry. Following on from the fundamental concept of symmetries, which was vital in the construction of the SM, this theory provides an underlying symmetry between fermions and bosons. The implications of such a theory are keenly desirable and could potentially provide solutions to a number of the open questions within the SM, in particular for the technical hierarchy problem. With the assumption that the couplings of the fermions and bosons to the Higgs are identical, then the fermionic and bosonic contributions combine in a neat cancellation and prevent the divergences in Higgs boson mass at any given energy scale, leaving only the bare Higgs mass. Since the Yukawa couplings are proportional to the

mass of the particle, the heaviest particles will contribute the most and hence the superpartners to the third generation quarks, the top- and bottom-squarks, are of key importance.

The discovery of the Higgs boson at the ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) experiments in 2012 completes the observation of the full spectrum of particles of the SM and presents an opportunity to search for BSM physics using this unique particle as a tool [1, 2]. This thesis reports the search for the pair production of the lightest supersymmetric partner of the bottom-quark ($\tilde{b}_1$) using 139 fb^{-1} of proton–proton data collected at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector. The final states considered contain no charged leptons, multiple jets originating from b -quark fragmentation and considerable missing transverse momentum, in complex decay chains involving the Higgs boson. The analysis imposes a set of kinematic and phenomenological requirements in order to isolate and identify the targeted process, whilst discriminating known SM processes that could mimic the same final state. Dedicated modelling is used to determine the expected number of events after these selections from each SM background process, where a significant excess in data events by comparison would indicate evidence of additional new physics processes.

The identification of b -jets is vital to the physics programme at the ATLAS experiment, and is of crucial significance for the aforementioned analysis. This technique relies on the ability of the innermost layers of the detector to identify secondary vertices within the jet substructure, where the *pixel detector* layers are vital. Whilst the current pixel detector performs effectively, it is designed to tolerate a maximum fluence of $\sim 10^{15} n_{\text{eq}}/\text{cm}^2$, and hence the current radiation tolerance is inadequate for the envisioned High Luminosity-LHC (HL-LHC). The HL-LHC project represents a unique challenge given the the substantial increase in event rate and track density, and the unprecedented levels of required radiation tolerance and timing resolution of the replacement inner detector, known as the Inner Tracker (ITk). Whilst proven hybrid technologies will instrument the innermost layers of ITk, the outer layers are expected to receive a fluence of $1.5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$, where this reduction in required radiation tolerance and event rate offers an opportunity to introduce and test a developing technology.

The High-Voltage CMOS¹ (HV-CMOS) technology is a novel pixel detector design based on CMOS technology that enables simpler devices with a reduced material budget by integrating some or all of the readout electronics directly into one chip, with view to a fully monolithic implementation. The multi-well CMOS structure allows the in-pixel electronics to be effectively shielded from the high bias voltage that significantly decreases the drift time of the collected charge. Given the redundancy of the dedicated readout chip, and hence the expensive bump-bonding process required to connect it to the pixel sensor, the greatly-simplified manufacturing process reduces the complexity and enables the production of cheap sensors. These sensors are therefore particularly well suited to large surface instrumentation of tracking detectors with high granularity sensors. Whilst a fully monolithic HV-CMOS device is the desired achievement, development of hybrid HV-CMOS pixel detectors that share the same sensor design, and hence charge collection properties, poses a preliminary step towards the full monolithic devices and represent an interesting option for future large scale tracking detectors in their own right. Prototype hybrid HV-CMOS devices were produced in various feature-sizes and substrate resistivities in order to perform a full detection efficiency and timing characterisation. The devices were tested, both before and after relevant irradiation increments, through extensive beam test measurements.

This thesis proceeds as follow: Chapter 1 contains a theoretical introduction to the existing SM of particle physics and a proposed extension, supersymmetry, which could explain physics beyond that of our current comprehension. Chapter 2 contains a description of the Large Hadron Collider and the ATLAS detector. Chapter 3 provides a description of the event reconstruction

¹Complimentary Metal Oxide Semiconductor.

in the ATLAS environment, with its recent performance also presented. Chapter 4 presents a search for new physics beyond the SM in complex decays involving the Higgs Boson with final state comprising of multiple b -tagged jets and missing transverse momentum. Chapter 5 reports on the future prospect of the HL-LHC project, focusing on the replacement Inner Tracker (ITk) of the ATLAS detector. Beam test results of a novel pixel detector design that is a potential candidate for the outer layers of the ITk are presented. Chapter 6 summarises and concludes the presented results.

Chapter 1

The Standard Model and Beyond

1.1 Fundamental Particles

What are the smallest building blocks of matter? A question first posed centuries ago and one which ultimately led to the scientific discovery of the atom, igniting the revolution of particle physics that dominated much of the 20th century. Atoms are the bound state of negatively charged electrons (e^-) orbiting a central nucleus consisting of positively charged protons (p) and electrically neutral neutrons (n). The electrons and nucleus are bound by the electromagnetic force, a low energy manifestation of Quantum Electrodynamics (QED). The protons and neutrons themselves are not fundamental particles. This is to say that they are not the smallest discernible components and are in fact bound states of *up* and *down* quarks: the proton consisting of (uud) and the neutron of (udd). The strong interaction between these quarks, formulated as Quantum Chromodynamics (QCD), is responsible for the formation of such so-called *hadrons*, and it is the residual effect of this force which causes atomic nuclei to form. The varying multiplicity of protons, neutrons and electrons and the quantum mechanical laws that enforce strict quantisations of the electronic structure give rise to a wealth of different elements, which are organised into the periodic table.

The weak interaction is the third of the fundamental forces of particle physics, and is responsible for the nuclear β decay and for the nuclear fusion process within the sun. In both the nuclear β decay and nuclear fusion an electrically neutral, almost massless particle known as the electron-neutrino (ν_e) is produced. Gravity is the fourth and final of the fundamental forces and despite its negligible contribution to physics at the atomic scale, it is responsible for the larger-scale structure of the universe. Almost all common physical phenomena can be accounted for by the electron, electron-neutrino and the up and down quarks, collectively referred to as the *first generation* of matter, and are capable of interactions via one or several of the strong, electromagnetic, gravitational and weak forces. To our current understanding, these particles are the fundamental building blocks of the low-energy universe; they are fundamental particles.

However, when searching higher energy regimes, as is accessible through the use of particle colliders, further complexity becomes apparent and the number of known fundamental particles increases. The Standard Model of particle physics is an elegant theory that describes the known fundamental particles and the forces by which they interact. It encompasses the complexity of the currently comprehended phenomena in our universe into just two types of particles: fermions and bosons. Fermions are particles of half-integer spin, implying that they follow Fermi-Dirac statistics and hence obey the Pauli Exclusion principle. Bosons are particles of integer-spin, which follow Bose-Einstein statistics.

1.2 The Standard Model

The Standard Model (SM) is a concise theory of interactions between the fermionic particles and three of the four fundamental forces: the strong force, electromagnetic and the weak force, where the inclusion of gravity is as of yet an unresolved challenge. The SM is constructed from a number of essential foundations: the Dirac equation of relativistic quantum mechanics, describing the dynamics of the fermions; Quantum Field Theory (QFT), which provides a mathematical description of the particles and their interactions; local gauge invariance, which dictates how these interactions are realised in nature; the Higgs mechanism of electroweak symmetry breaking, which is responsible for the generation of the particle masses; and the vast wealth of experimental data which was key to the development and guidance of the theory [3]. The fermionic and bosonic content of the SM are presented in Tables 1.1 and 1.2 respectively.

The fermions of the SM can be categorised into particles that can interact via the strong force, known as *quarks*, and particles that cannot, known as *leptons*. They can be yet further subdivided into three generations of increasing mass, whereby the electron and electron-neutrino, and the up and down quarks are the leptons and quarks respectively which form the first generation. The particles of the second and third generation are unstable and decay to lighter particles and are commonly produced in high-energy particle collisions. Each generation is composed of two doublets, one for the leptons and one for the quarks.

For the leptons, the doublet is formed of an electromagnetically charged particle (e, μ, τ) and its corresponding, electrically-neutral lepton-neutrino (ν_e, ν_μ, ν_τ). QED is the mathematical formulation of this interaction, whereby particles carrying an electric charge are able to interact via this force. It is the corresponding quantum counterpart of the classical electrodynamics and provides a complete description of matter-light interactions [4, 5].

The quark doublet is formed of an up-type quark (u, c, t), which carry an electromagnetic charge of $+2/3$, and a down-type quark (d, s, b) which have an electromagnetic charge of $-1/3$. Quarks also carry another conserved quantum number referred to as *colour* [6]. QCD is the mathematical formulation of this interaction, whereby coloured particles are able to interact via this force. Quarks can exist in either a red, green or blue colour state, however experimental results suggest that coloured particles do not exist in nature and hence quarks cannot exist as free particles. This phenomenon is referred to as *colour confinement* and is the reason why quarks exist only in colourless, bound states known as hadrons - they are said to be confined. Colour confinement comes as a consequence of the dependency of the QCD coupling strength with the momentum transfer of the interaction Q^2 ,

$$g_s^2(Q^2) = \frac{4\pi}{\beta_0 \ln\left(\frac{Q^2}{\Lambda_{\text{QCD}}^2}\right)} \quad (1.1)$$

where the QCD coupling constant, g_s , can be redefined to an effective ‘fine-structure constant’ for QCD as $\alpha_s = g_s^2/4\pi$. Figure 1.1 presents the experimental measurements of the QCD coupling constant as a function of the momentum transfer. At low energies (large distances), where the momentum transfer tends to the QCD scale (Λ_{QCD}^2), the QCD coupling strength increases. This property can be further understood by introducing an effective potential between two quarks. It is empirically found that the potential follows the behaviour $\propto 1/r$ at short distances and an almost linearly rising potential $\propto r$ at larger distances [7]. Hence, with increasing distances, the energy required for further separation eventually becomes sufficiently high so that it is energetically more favourable to produce new particles from the vacuum. As a consequence, this *hadronisation* process begins to build new colour-neutral bound states: either a meson, a bound state of quark anti-quark ($q\bar{q}$) with the same colour, or as a baryon, a bound state of three quarks

Fermions					
Generation	Name	Symbol	Spin	Charge [e]	Mass
I	Up-quark	u	1/2	+2/3	2.2 MeV
	Down-quark	d	1/2	-1/3	4.7 MeV
	Electron	e^-	1/2	-1	0.511 MeV
	Electron-neutrino	ν_e	1/2	0	< 2 eV
II	Charm-quark	c	1/2	+2/3	1.27 GeV
	Strange-quark	s	1/2	-1/3	96 MeV
	Muon	μ^-	1/2	-1	105.7 MeV
	Muon-neutrino	ν_μ	1/2	0	< 0.19 eV
III	Top-quark	t	1/2	+2/3	172.9 GeV
	Bottom-quark	b	1/2	-1/3	4.18 GeV
	Tau	τ^-	1/2	-1	1776.8 MeV
	Tau-neutrino	ν_τ	1/2	0	< 18.2 eV

TABLE 1.1: Fermionic particle content of the SM. Particle masses taken from [24].

Bosons					
Interaction	Name	Symbol	Spin	Charge [e]	Mass
Strong	Gluon	g	1	0	0
Electromagnetic	Photon	γ	1	0	0
Weak	W-boson	$W^\pm$	1	± 1	80.4 GeV
Weak	Z-boson	Z	1	0	91.2 GeV
-	Higgs boson	h	0	0	125.1 GeV

TABLE 1.2: Bosons of the SM. Particle masses taken from [24].

or anti-quarks (qqq or $\bar{q}\bar{q}\bar{q}$) with differing colours, where a commonly encountered example of a baryon is a proton (uud). When the QCD coupling constant decreases at high values of Q^2 (small distances), the quarks are said to be quasi-free. This behaviour is known as *asymptotic freedom* and it is the regime where QCD calculations can be computed perturbatively (pQCD). Therefore bare quarks and gluons are not observed directly in nature and instead are able to radiate energy through emission of additional gluons up until an energy scale where confinement occurs and then the hadronisation process commences. Experimentally, this is observed as a flow of collimated hadrons, known as a *jet*.

While the fermions are particles that constitute matter, the bosons are responsible for the interactions between them. Each of the fundamental forces of the SM has an associated boson, which is responsible for mediating interactions between fermions via this particular force. During an interaction the associated boson is exchanged between the fermions.

The electroweak interaction is a fundamental component of the SM. Initially, the weak and electromagnetic interactions were regarded as separate forces with corresponding theories. The electromagnetic interaction was described by the aforementioned QED, and the weak interaction was initially described by an effective theory that was consistent at low energies and is known as the Fermi theory, or Quantum Flavour Dynamics. This theory stipulated that charged current

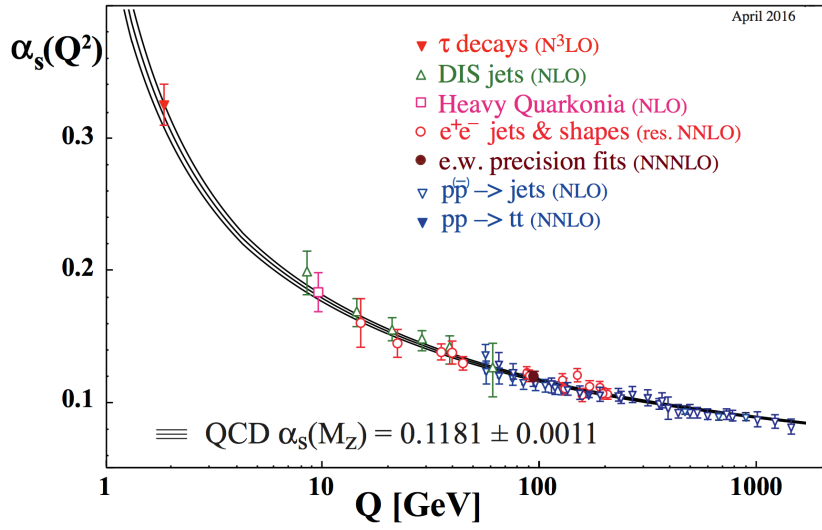


FIGURE 1.1: Theoretical predictions and experimental measurements of the QCD coupling constant (α_s) as a function of the momentum transfer (Q^2) of a process. Taken from [7].

interactions could be approximated by a point-like interaction. However, at energies approaching the electroweak scale (~ 100 GeV), this theory breaks down. Empirical evidence revealed that only left-handed chirality particles were involved in the charged current interaction, which led to the introduction of the *weak-isospin* quantum number T [8]. Of this, it is the third-component of the weak isospin, T_3 , that the forces couple to. Left-handed fermions are then grouped into doublets with $T = 1/2$ and thus $T_3 = \pm 1/2$. All right-handed fermions form a singlet with $T = 0$, $T_3 = 0$ and as a result do not interact via charged current interactions. The right-handed neutrino is not included as this particle has never been experimentally detected and is predicted to interact solely via the gravitational interaction. To describe the electromagnetic interaction, which couples to both left- and right-handed particles, the *hypercharge*, Y_w , is introduced, and is defined as $Q = T_3 + Y_w/2$, where Q is the electric charge. An important aspect of this unification is that the weak component couples only to the left-handed weak isospin doublets of the SM, whereas the hypercharge component can act on both the left- and right-handed components. This unification of the electromagnetic and weak forces as the electroweak interaction was proposed by Glashow, Salam and Weinberg [8–11].

The concept of symmetry is fundamental to the SM, where in particular Noether's theorem states that for each conserved symmetry there is a connected conserved quantity. The mathematical structure of the SM is founded on this principle and expressed as a QFT [12]. All fundamental particles are described as excitations of quantum fields that exist at all points in space-time. Fermions are described by fermion fields, $\psi(x)$, also known as Dirac-spinors, and gauge bosons are described by vector fields $A_\mu(x)$. The SM is built by applying local gauge invariance to the three forces by introducing additional bosonic gauge fields, whereby the interactions between the fermions and the bosons arise naturally. Local gauge invariance implies that the interactions are invariant under a local gauge transformation. The number of bosonic gauge fields needed to be introduced is equal to the number of generators of the symmetry group, namely the number of physical bosons of the interaction. Following from this, the SM can be formulated as a QFT with an underlying $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry, where each of the components correspond to the symmetry group that generates the interactions: $SU(3)_C$ corresponding to colour, $SU(2)_L$ corresponding to weak-isospin and $U(1)_Y$ corresponding to the hypercharge.

$SU(3)_C$ is the gauge group of QCD and provides the description of the strong interaction through a colour charge symmetry. The gluon is the mediator of the strong interaction and is a massless,

electrically neutral boson. Gluons themselves are coloured particles and realise themselves as eight distinct bosons. Gluons couple to particles with colour charge and hence the quarks are the only fermions to interact via this force.

The unification of the weak and electromagnetic forces led to the formulation of the electroweak interaction, described by the $SU(2)_L \times U(1)_Y$ symmetry group, where the subscripts L and Y denote the weak-isospin and hypercharge respectively. The corresponding four gauge bosons are represented as W_1, W_2, W_3 for $SU(2)_L$ and B for $U(1)_Y$. The W_i triplet and the B boson mix to form the physical bosons: the photon (γ), the Z^0 boson and the $W^\pm$ bosons. The photon is the mediator of the electromagnetic interaction and is a massless, electrically neutral boson. It couples to electromagnetic charge, and hence electrically charged particles can interact via the electromagnetic interaction: the quarks and charged leptons. The $W^\pm$ and Z^0 bosons are the mediators of the weak force. The $W^\pm$ bosons are electrically charged, massive particles that are responsible for mediating the weak charged current interaction. The Z^0 boson is an electrically neutral, massive particle that is responsible for mediating the weak neutral current interaction. As a consequence of gauge invariance, the mediators of the fundamental interactions should be massless. Unlike the photon and the gluon, the W and Z bosons are massive, and as a consequence the weak force is short range ($< 10^{-16}\text{m}$).

In order to account for the non-zero mass of the W and Z bosons a complex scalar field known as the Higgs field was introduced to include the Brout-Englert-Higgs mechanism, responsible for generating the electroweak boson masses via spontaneous symmetry breaking of the electroweak sector [13–15]. The Higgs field permeates through the universe and interacts with particles via the Higgs boson and provides mass to the massive particles. The Higgs boson is an unusual boson in the SM. It is the only known fundamental scalar ($s = 0$) and it is not associated to one of the fundamental interactions. The Higgs boson is instead an excitation of the Higgs field. The Yukawa couplings between the fermions and the Higgs boson are proportional to the mass of the fermion.

The SM has proved to be a very successful theory and has been experimentally verified by many experiments covering a wide energy range. Measurements performed by the ATLAS experiment at the LHC confirm the predictions of the SM over several orders of magnitude in production cross-section, as can be seen in Figure 1.2. Despite its success, the SM is inherently an incomplete theory and is more of an effective field theory that describes a low-energy regime, albeit rather accurately, and is believed to be a part of a grander theory. There are observable physical phenomena that the SM inadequately explains and hence physics beyond the SM (BSM) is inevitable.

1.3 Open Questions in the Standard Model

Attempts have been made to carry a further unification of the forces and combine the electroweak and strong forces into a new symmetry that manifests itself at very high-energies. The scale at which this is predicted to occur is referred to as the scale of Grand Unified Theories and is thought to be in the order of $E_{\text{GUT}} \simeq 10^{16} \text{ GeV}$ [16]. The apparent problem in hierarchy between the scale at which is expected to occur and that of the electroweak scale $E_{\text{EW}} \simeq 10^2 \text{ GeV}$ is a question of *naturalness* and is commonly referred to as the Hierarchy problem [17, 18]. The concept of naturalness is one that expects the parameters of a theory to take relative values of order one. This is to say that these relative scales appear to be ‘unnatural’, since it requires a large amount of fine-tuning of the parameters of the SM in order to correctly replicate what is observed through experimentation [19]. This situation is only worsened when considering the energy scales at which gravity becomes equally as strong as the other forces at the Planck scale

Standard Model Production Cross Section Measurements

Status: July 2018

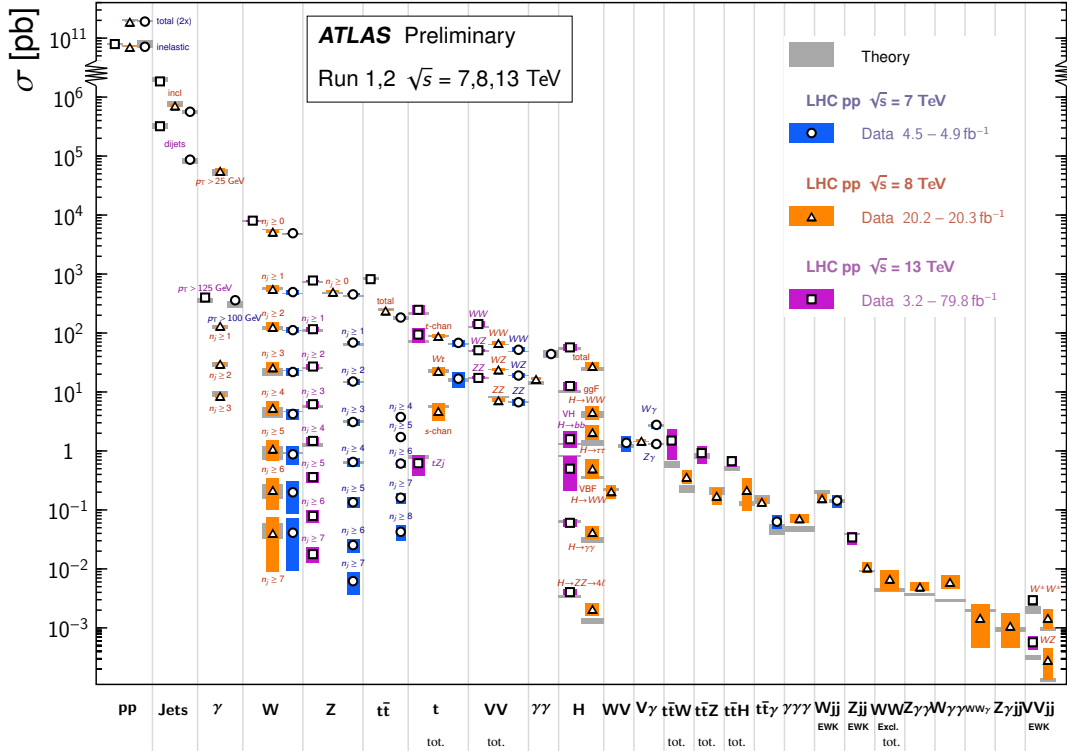


FIGURE 1.2: An overview of SM total and fiducial production cross-section measurements in comparison with the theoretical expectations at ($\sqrt{s} = 7, 8, 13$ TeV) centre mass energy. Taken from [73].

$E_{\text{Planck}} \simeq 10^{19}$ GeV, where the ratio of the electroweak symmetry breaking scale and the Planck scale is very small ($E_{\text{EW}}/E_{\text{Planck}} \simeq 10^{-17}$).

The technical hierarchy problem poses an unresolved issue regarding the mass of the Higgs boson. Particles that interact with the Higgs field contribute to the physical Higgs mass through quantum loop corrections and is formulated in Equation 1.2,

$$\Delta m_H^2 \simeq -\frac{|\lambda_f|^2}{16\pi^2} \left[2\Lambda^2 + 6m_f^2 \ln \left(\frac{\Lambda}{m_f} \right) + \dots \right] \quad (1.2)$$

where Δm_H is the correction to the physical Higgs boson mass and λ_f the Yukawa coupling of a fermion of mass m_f . To regulate the loop integral, an energy cutoff scale Λ is introduced. At energies typical of the electroweak scale, these corrections are negligible, however, if the energy cutoff scale considered is that of the Planck scale, then the quadratic divergences to the Higgs mass become problematic. Given that these corrections are proportional to the mass of the fermion, then the fermions of highest mass contribute most significantly. For the top quark, $\lambda_f \simeq 0.94$ and hence at the Planck scale the correction itself would be thirty times larger than the required value of m_H . This is direct evidence that there must exist new physics between the electroweak and Planck scale that is likely to introduce a cancellation mechanism to these divergent corrections to the mass and hence would account for the discrepancy in theoretical and observed mass of the Higgs boson.

It was once thought that most of the mass in the universe resides in the luminous objects that are clustered primarily in the centre of galaxies. However, there is substantial evidence to

suggest otherwise [20, 21]. Through measurements of the velocity distributions of galaxies as a function of the distance from the galaxy centre, r , it can be seen that the mass is distributed by approximately $M(r) \propto r$, instead of the expected $M(r) \propto r^{-1/2}$. Hence from this linear dependence, it can be inferred that a significant proportion of the mass of a galaxy is non-luminous and is thus referred to as dark matter. The existence of dark matter in the universe provides a compelling necessity for a suitable particle candidate, with all of the SM particles having already been excluded. Of the theoretically motivated candidates, Weakly Interacting Massive Particles (WIMPs) are a notable suggestion [22].

As the universe expanded and cooled, the necessary creation energy for each particle-antiparticle pair became increasingly more unattainable. After the freeze-out, the remaining particle-antiparticle pairs annihilated to produce energy. In order to avoid this and thus observe the abundance of existing matter in the universe, there must either be an asymmetry that allowed some matter to remain, or the cross-section must be so low that the probability of particle-antiparticle pairs annihilating would be sufficiently small so as to allow a residual density to exist. When calculated, the cross-section necessary to allow this density to exist roughly coincides with the theoretical WIMPs, which would interact via the electroweak force. This coincidence in scales is known as the WIMP miracle. The matter anti-matter asymmetry in the universe is yet unexplained in the SM.

Another significant problem of the SM is that neutrinos are known to exist in only one helicity state and are therefore assumed to be massless. Although no direct measurement of the neutrino mass has yet been made, the observation of neutrino flavour oscillations is indicative of non-zero neutrino masses. Indirect detection of the electron neutrinos produced in the sun led to an unexpected deficit, suggesting that neutrinos are able to oscillate between flavour states and is governed by the Pontecorvo-Maki-Nakagawa-Sakata matrix [23, 24].

1.4 Supersymmetry

Amongst the many BSM theories intending to provide extensions to the existing SM framework, one of the more notable is called supersymmetry [25–35]. Following on from the fundamental concept of symmetries, which was vital in the construction of the SM, this theory provides an underlying symmetry between fermions and bosons. It is possible to introduce an operator Q responsible for the transformation between a fermionic and bosonic state.

$$Q | \text{Boson} \rangle \propto | \text{Fermion} \rangle, \quad Q | \text{Fermion} \rangle \propto | \text{Boson} \rangle \quad (1.3)$$

This new symmetry introduces a group orthogonal to the SM that can be expressed as $SU(3)_C \times SU(2)_L \times U(1)_Y \times SUSY$. The implication of such a symmetry is that it associates a fermionic (bosonic) partner to every SM boson (fermion), referred to as a superpartner. Since it is orthogonal, the mass and quantum numbers are unaffected and remain identical under a supersymmetric transformation, differing only in their spin by a half unit, hence determining whether they are fermionic or bosonic in nature. As a result, the observed particles and hypothetical superpartners can be placed into a supermultiplet: either a chiral (scalar) multiplet or a gauge (vector) multiplet.

The SM fermions and their spin-0 superpartners form the components of the chiral multiplet, and hence the matter content is formed by three generations of chiral multiplets. Since the SM fermions are chiral spinors and that the number of degrees of freedom must remain equal within the fermionic and bosonic sector, each fermion has two scalar partners, one partner to

the left-handed fermions $\tilde{f}_L$ and the other for the right-handed fermion $\tilde{f}_R$. The superpartners experience the same gauge interactions as the SM partners. The naming convention for the supersymmetric particles in the chiral multiplet is to prefix an ‘s-’, for scalar. By example, the supersymmetric partner to the bottom-quark is the *sbottom*.

The vector bosons of the SM reside in gauge supermultiplets with their superpartners. Generically, these superpartners are referred to as gauginos. The nomenclature for the supersymmetric particles in the gauge multiplet is to introduce a suffix ‘-ino’. For example, the supersymmetric partner to the SM gluon is the *gluino*. The spin-1 gauge bosons associated with the electroweak symmetry are the W_1 , W_2 , W_3 and B . The superpartners to these are referred to as *winos* and *bino* and are denoted as $\tilde{W}_1$, $\tilde{W}_2$, $\tilde{W}_3$ and $\tilde{B}$.

The SM contains one Higgs doublet, however as a consequence of charge conservation, two Higgs doublets must be included in the SM *a priori* to the inclusion of supersymmetry. A fermionic partner of a Higgs chiral supermultiplet must be a weak isodoublet with weak hypercharge $Y = \pm 1/2$. Only the $Y = 1/2$ Higgs chiral supermultiplet has the requirements to provide mass to the up-type quarks. Whereas only the $Y = -1/2$ Higgs chiral supermultiplet has the requirements to provide mass to the down-type quarks. These two doublets therefore introduce four gauge eigenstates: H_u^0, H_u^+ and H_d^0, H_d^- , which then mix to form the mass eigenstates: h^0, H^0, A^0 and $H^\pm$. Of these, it is h^0 which is the SM Higgs boson. Of this extended Higgs sector, it is the gauge eigenstates that are placed into a supermultiplet with their superpartners and are referred to as Higgsinos, $\tilde{H}_u^0, \tilde{H}_u^+, \tilde{H}_d^0, \tilde{H}_d^-$.

This completes the gauge group and particle content of a phenomenologically viable extension of the SM, where the minimal content required to form a consistent theory is known as the Minimal Supersymmetric SM (*MSSM*) and is presented in Tables 1.3 and 1.4 [36, 37].

By significantly increasing the particle content, supersymmetry introduces a coupling that would lead to a proton decay within seconds, whereas stringent limits exist on the proton lifetime set through experiment [38]. These undesirable couplings can be eliminated by imposing invariance under a new symmetry, known as R-parity [39]. This new discrete symmetry is defined by,

$$R = (-1)^{3(B-L)+2S} \quad (1.4)$$

where B , L and S are the baryon number, lepton number and spin respectively. R-parity is conserved in all interactions. SM particles have an R-parity of $R = +1$ and all supersymmetric particles have $R = -1$. This has crucial phenomenological implications: supersymmetric particles are only produced in pairs in order to conserve this quantum number, and as supersymmetric particles are unstable they will eventually decay into lighter sparticles where the lightest supersymmetric particle, referred to as the LSP, is stable since it can no longer decay and conserves R-parity.

The introduction of many new particles also introduces a wealth of free parameters in the form of masses, phases and mixing angles. These 105 free parameters make the phenomenological study of all possible supersymmetric models an almost hopeless task. However, motivated experimental or theoretical constraints can be applied, significantly reducing the model to just 19 free parameters. This 19-parameter model is referred to as the ‘phenomenological’ *MSSM*, or *pMSSM* [40–42]. The parameters describing the *pMSSM* are presented in Table 1.5. The *pMSSM* provides a simpler framework that is phenomenologically testable through experiment.

Name	Symbol	spin 0	spin $\frac{1}{2}$	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks ($\times 3$ families)	Q	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	$(3, 2, \frac{1}{6})$
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 1, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 1, \frac{1}{3})$
sleptons, leptons ($\times 3$ families)	L	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$	$(1, 2, -\frac{1}{2})$
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ H_u^0)$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(1, 2, +\frac{1}{2})$
	H_d	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(1, 2, -\frac{1}{2})$

TABLE 1.3: Chiral supermultiplets in the Minimal Supersymmetric SM (*MSSM*). The Table contains the eigenstates after the supersymmetric transformation and do not represent the mass eigenstates [29].

Name	spin- $\frac{1}{2}$	spin- 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(8, 1, 0)$
winos, W bosons	$\tilde{W}^\pm \ \tilde{W}^0$	$W^\pm \ W^0$	$(1, 3, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(1, 1, 0)$

TABLE 1.4: Gauge supermultiplets in the Minimal Supersymmetric SM (*MSSM*). The Table contains the eigenstates after the supersymmetric transformation and do not represent the mass eigenstates [29].

1.5 Supersymmetric Mass Eigenstates

In the SM the electroweak bosons arise from the mixing of the W_i triplet and B gauge bosons. Analogously, mixing between the sparticles may occur and is dependent on the free parameters of the *MSSM*. The supersymmetric partners previously introduced in the scalar and vector multiplets do not necessarily represent the physical mass eigenstates and in reality mixing between the gauge eigenstates occurs. Presented in Table 1.6 are the gauge and mass eigenstates of the supersymmetric particles and the extended Higgs sector [29].

The neutral electroweak gauginos and neutral higgsinos mix to form neutral particles known as the neutralinos, $\tilde{\chi}_{1-4}^0$. In the models considered in this thesis, the lightest neutralino $\tilde{\chi}_1^0$ is considered the LSP. As a consequence of its minimal interaction, the presence of the $\tilde{\chi}_1^0$ can only be inferred by missing transverse momentum ($\mathbf{p}_T^{\text{miss}}$) in the detector¹. Mixing also occurs between the charged electroweak gauginos and charged higgsinos to produce four charged charginos, $\tilde{\chi}_{1,2}^\pm$. The amount of mixing between the binos, winos and higgsinos is driven by the bino mass (M_1), the wino mass parameter (M_2) and the higgsino mass parameter (μ).

Within the squark and slepton sector, the amount of mixing is proportional to the mass of the relevant SM particle and hence is only significant for the third generation: the top and bottom-squarks and the tau slepton [29]. The gauge eigenstates of the top squark are denoted as $\tilde{t}_L, \tilde{t}_R$, where L and R refer to the handedness of the SM partner. The gauge eigenstates mix to produce the mass eigenstates $(\tilde{t}_1, \tilde{t}_2)$, where the $\tilde{t}_1$ is deemed the lighter state of the two by convention.

¹detailed in Chapter 3

Parameter	Description
$ M_1 , M_2 , M_3 $	Bino, Wino, Gluino mass parameter
$M_{\tilde{q}}, M_{\tilde{u}_R}, M_{\tilde{d}_R}, M_{\tilde{l}}, M_{\tilde{e}_R}$	1 st and 2 nd generation sfermion masses
$M_{\tilde{Q}}, M_{\tilde{t}_R}, M_{\tilde{b}_R}, M_{\tilde{L}}, M_{\tilde{\tau}_R}$	3 rd generation sfermion masses
A_t, A_b, A_τ	3 rd gen. trilinear couplings
μ	Higgsino/ Higgs mass parameter
$\tan \beta$	Ratio of Higgs vacuum expectation values
M_A	Pseudo-scalar Higgs boson mass

TABLE 1.5: Overview of the parameters of the $pMSSM$ [29].

The superpartners of the bottom-quark follow a similar procedure, hence similar mixing occurs with the bottom-quark gauge eigenstates in order to produce the mass eigenstates $(\tilde{b}_1, \tilde{b}_2)$. If the $\tilde{t}_1$ is mostly composed of the left-handed state, then the bottom-squark can also be light since the masses of the two states are controlled by a single mass parameter [43]. Likewise, the two mass eigenstates of the superpartner to the tau lepton are denoted $(\tilde{\tau}_1, \tilde{\tau}_2)$.

1.6 Implications of Supersymmetry

The implications of such a theory are keenly desirable and could potentially provide solutions to a number of the open questions within the SM. As described in Section 1.3, the technical hierarchy problem arises from loop corrections to the Higgs mass causing significant divergences. However, with the inclusion of the superpartners, for each SM correction term there is an analogous supersymmetric contribution. The correction to the mass of the Higgs boson arising from the coupling of a fermion to the Higgs is presented in Equation 1.2. The contribution now arising from the scalar superpartners is presented in Equation 1.5,

$$\Delta m_H^2 \simeq \frac{\lambda_s}{16\pi^2} \left[\Lambda^2 - 2m_s^2 \ln \left(\frac{\Lambda}{m_s} \right) + \dots \right] \quad (1.5)$$

where Δm_H is the correction to the physical Higgs boson mass and λ_s is the Yukawa coupling of a scalar of mass m_s . With the assumption that the couplings of the fermions and bosons to the Higgs are identical, i.e. $\lambda_s = |\lambda_f|^2$, then the fermionic and bosonic contributions combine in a neat cancellation and prevent the divergences in Higgs boson mass at any given energy scale, leaving only the bare Higgs mass.

As previously discussed in Section 1.3, particles with the highest Yukawa couplings contribute most significantly to the loop corrections to the Higgs mass. Since this Yukawa coupling is proportional to the mass of the particle, the heaviest particles will contribute the most and hence the superpartners to the third generation quarks, the top- and bottom-squarks, are of key importance.

The understanding of dark matter is one of the priorities of modern particle physics. Of the proposed solutions, Weakly Interacting Massive Particles (WIMPs) are amongst the most compelling, where it may be possible to produce them directly at LHC. In R-parity conserving supersymmetry models, the lightest neutralino ($\tilde{\chi}_1^0$) is electrically neutral and would interact

Names	spin	R-parity	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0, H_u^+, H_d^0, H_d^-$	$h^0, H^0, A^0, H^\pm$
sleptons	0	-1	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$	same
			$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$	same
			$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$
squarks	0	-1	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$	same
			$\tilde{c}_L, \tilde{c}_R, \tilde{s}_L, \tilde{s}_R$	same
			$\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
neutralinos	1/2	-1	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
charginos	1/2	-1	$\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{H}_d^\pm$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
gluino	0	-1	$\tilde{g}$	same

TABLE 1.6: Gauge and mass eigenstates of the supersymmetric particles and the extended Higgs sector [29].

solely via the gravitational interaction, and so provides an attractive non-baryonic candidate for dark matter [22]. In this thesis, the $\tilde{\chi}_1^0$ is assumed to be the LSP.

Despite the formalism of supersymmetry which resolves in distinct, theoretical mass eigenstates of the superpartners, it is a striking feature that none of these superpartners have yet been observed. If supersymmetry was a perfect symmetry, then a supersymmetric electron ($\tilde{e}$) would have already been discovered with a mass equal to that of the SM electron. Supersymmetry, therefore, must be a broken symmetry and hence any supersymmetric model which aims to provide a realistic description of nature must contain a breaking mechanism, consequently leading to the supersymmetric partners being heavier than their SM partners. The breaking mechanism must be broken spontaneously, but *softly*, so that the neat cancellation effect of the loop corrections to the Higgs boson mass remains, hence ensuring that the attractive theoretical features of such a theory are not lost. Soft breaking would ensure that the high-energy (hence highly divergent) processes would continue to respect the symmetry, while the low energy-processes would violate it and would allow - and in fact cause - loop corrections to the Higgs mass, however these are negligible given the low energy [44]. This soft breaking is achievable if the masses of the top- and bottom-squarks are close to that of their SM partners, namely around the electroweak scale, and hence reiterates the desire for naturalness - a desire for the ratio of the masses of the third generation SM particles and their superpartners to be of order one. If this is the case, their production would be abundant at the LHC.

1.7 Bottom Squark Phenomenology

In high energy hadron colliders, such as the LHC, the dominant production processes of sparticles are those involving coloured particles, namely squarks and gluinos. At the LHC, the bottom-squark $\tilde{b}_1$ is produced via two mechanisms:

Gluino Decays	$pp \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{b}_1\tilde{b}_1 \quad \text{or} \quad \tilde{g} \rightarrow \tilde{b}_1\tilde{b}_1$
Direct Pair Production	$pp \rightarrow \tilde{b}_1\tilde{b}_1$

The production cross-section as a function of the mass for both mechanisms is presented in Figure 1.3. In scenarios where R-parity is conserved, the squark pair production ($\tilde{q}\tilde{q}$), gluino-squark production ($\tilde{g}\tilde{q}$) and gluino pair production ($\tilde{g}\tilde{g}$) are the most dominant channels. Although the production cross-section of the bottom-squark pair production is not presented in Figure 1.3, it can be approximately represented by the direct top squark pair production given. The production via gluino decays can only occur if the mass of the gluino is sufficiently high so as to be able to decay into a $\tilde{b}_1\tilde{b}_1$ pair. Therefore, the single gluino splitting to a bottom-squark pair becomes significantly suppressed. From Figure 1.3 it can be deduced that the dominant decay process is dependent on the masses of both the bottom-squark and the gluino. With low mass degeneracy between the gluino and bottom-squark, the gluino pair production is the dominant production process, whereas at higher mass splitting, the direct bottom-squark pair production becomes dominant [46–48, 164].

The cross-section for pair production of third generation squarks ($\tilde{t}_1, \tilde{b}_1$) at the LHC is significantly less than that of the first and second generations, with a factor between 10^{-3} - 10^{-1} for the same mass and centre-of-mass energy. This is because the parton distribution functions of the protons at the LHC contain negligible proportions of bottom-quarks and no top quarks and hence many of the dominant first order production mechanisms either do not occur or are negligible. It is therefore apparent that substantial data is required in order to successfully study these potential, yet rare processes [49, 50].

Once supersymmetric particles have been produced, they will decay into a number of potential final states, producing an experimental signature of interest. A technique often used to reduce the complexity of searching for supersymmetry models, is to construct a so-called *simplified model* [51–53]. These are specifically constructed in order to include only a few new particles and interactions. These models can be described by a small number of parameters that are intentionally measurable at collider experiments, such as particle masses, production cross-sections and branching fractions. These models are particularly important as they provide a scenario in which the discovery of such particles is feasible given the current experimental capabilities. They often deploy well motivated constraints on various phenomenological features, allowing for experimental tests of particular aspects of a model. The sensitivity to any new physics as a function of one of these parameters is then presented, typically over the phase space of the particle mass. Though these results produce topology-based limits, they can also be reinterpreted to more general models that produce the same topology. Simplified models are often designed using the following assumptions:

- Only one decay mode is considered and is assumed to have a branching ratio of 100%.
- The masses of the sparticles involved in the decay chain are assumed to be decoupled.
- The masses of the sparticles are treated as free parameters.
- Commonly exploit motivated mass assumptions.

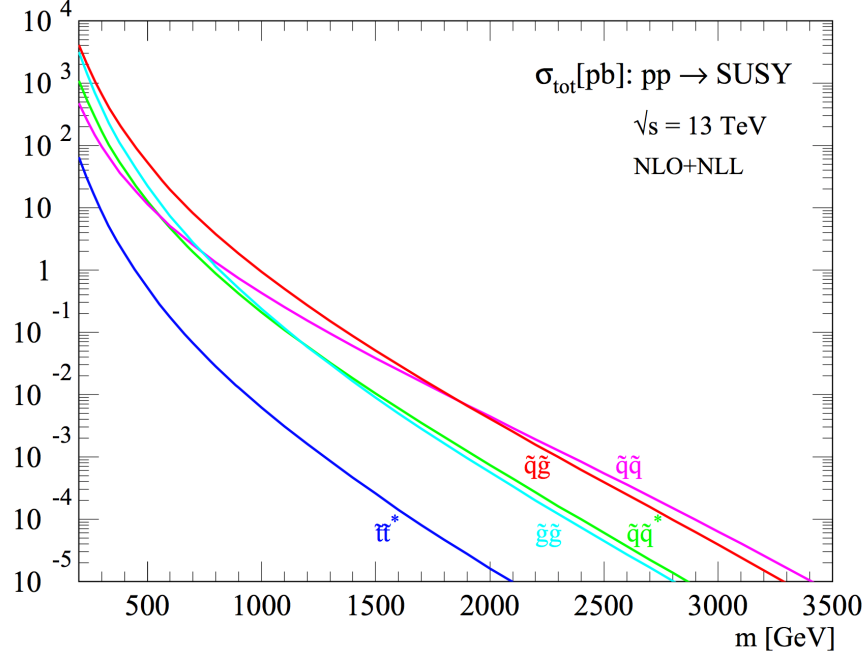


FIGURE 1.3: NLO+NLL production cross-sections for the case of equal degenerate squark and gluino masses as a function of mass at $\sqrt{s} = 13$ TeV [74].

A simplified model is used for the interpretation of the results of a search for new physics through complex decay chains of the bottom-squark in final states containing multiple jets originating from the fragmentation of b -quarks (b -jets) and missing transverse momentum. Figure 1.4 presents the schematic diagram of the targeted scenario. A unique signature of pair produced scalar bottom-squarks is targeted, where the simplified model used assumes they are the only supersymmetric particle produced at the LHC and that they decay with a 100% branching ratio ($\mathcal{B}$) to a b -quark and $\tilde{\chi}_2^0$. The $\tilde{\chi}_2^0$ then subsequently decays with a 100% branching ratio to a Higgs boson and a $\tilde{\chi}_1^0$, the latter of which is stable and the LSP. The Higgs bosons in the simplified model are the SM Higgs bosons. Since the dominant decay of the Higgs is to $b\bar{b}$, with $\mathcal{B}(h \rightarrow b\bar{b}) = 58\%$, a unique signature of large missing transverse momentum and up to six b -jets may be present [54].

As previously mentioned in Section 1.4, the composition of the neutralinos and charginos is dependent on the parameters $|\mu|$, $|M_1|$ and $|M_2|$. When $|\mu| \ll |M_1|, |M_2|$, the neutralinos and charginos are *higgsino-like*, leading to a small mass splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0) < \mathcal{O}(10)$ GeV. In this case, the decays of the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are dominated by Z^* and W^* decays respectively, leading to soft decay products that are difficult to measure in the ATLAS detector. In these scenarios $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ decays are highly suppressed due to the mass splitting.

In scenarios in which $|M_1| \leq |\mu|$ and $|M_2| > |M_1|$, the lightest neutralino $\tilde{\chi}_1^0$ is mostly bino. This leads to a stronger coupling of $h\tilde{\chi}_2^0\tilde{\chi}_1^0$ than $Z\tilde{\chi}_2^0\tilde{\chi}_1^0$ and hence $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ decays become the dominant decay mode. Figure 1.5 shows an example of $pMSSM$ scenarios in which the $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0)$ is non-zero. The plots show the higgsino (Figure 1.5(a)), wino (Figure 1.5(b)) and bino (Figure 1.5(c)) fraction of the LSP as a function of $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0)$. The results show that models in which $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0)$ is large the $\tilde{\chi}_1^0$ is bino-like.

The $\tilde{\chi}_2^0$ is wino-higgsino-like in such models in which $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) > 0.8$, as made evident in Figure 1.6. Figure 1.6(b) shows the higgsino fraction and the wino fraction of the $\tilde{\chi}_2^0$ on the x-axis and y-axis respectively. Models that are almost pure higgsino $\tilde{\chi}_2^0$ or pure wino $\tilde{\chi}_2^0$ are more common, yet many models exist with mixed fractions.

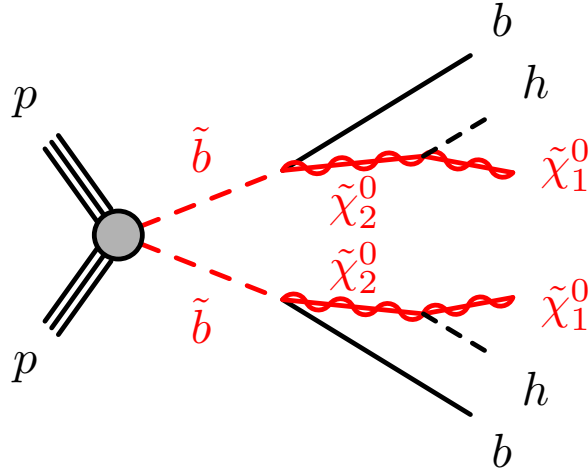


FIGURE 1.4: Graphical representation of the signal phenomenology targeted by the analysis presented in this thesis. Scalar bottom-quarks are produced in pairs and subsequently decay to $b\tilde{\chi}_2^0$ with 100% branching ratio. The two $\tilde{\chi}_2^0$ particles decay to $h\tilde{\chi}_1^0$ also with 100% branching ratio.

The decay processes and hence final state topology are therefore directly dependent on the composition of the gauginos. This allows for more complex searches for the bottom-squark.

1.8 Constraints on Supersymmetry

Supersymmetry introduces a vast phase-space that could be realised in nature. The *MSSM* offers an initial simplification, however it still poses an extraordinary task when searching for new particles. Since the beginning of data taking, the LHC has recorded a substantial amount of data allowing for extensive supersymmetry searches, however no significant evidence has yet been observed. In the absence of evidence, limits can be placed upon the models in question in order to exclude mass scenarios from the possible phase-space. Limits produced in recent years by the ATLAS and CMS collaborations have significantly extended the exclusions set by the LEP [55–58] and Tevatron experiments [59–62] that were decommissioned in the year 2000 and 2011 respectively, where the LEP experiment has since been replaced by the LHC.

The majority of previous searches for the scalar partner of the bottom-quark performed using the ATLAS detector focus on the direct pair production of $\tilde{b}_1$ [63–69]. A summary of the exclusion limits on the bottom-squark mass set by the ATLAS experiment is shown in Figure 1.7. Presented is the exclusion limit at 95% Confidence Level (CL_s) in the $(\tilde{b}_1, \tilde{\chi}_1^0)$ mass plane for direct bottom-squark pair production. The lightest neutralino ($\tilde{\chi}_1^0$) is assumed to be the LSP. The exclusion limit presents a combination of various analyses, where the different simplified models considered are shown along with the different parameterisations of the intermediate particles in the models [70–72].

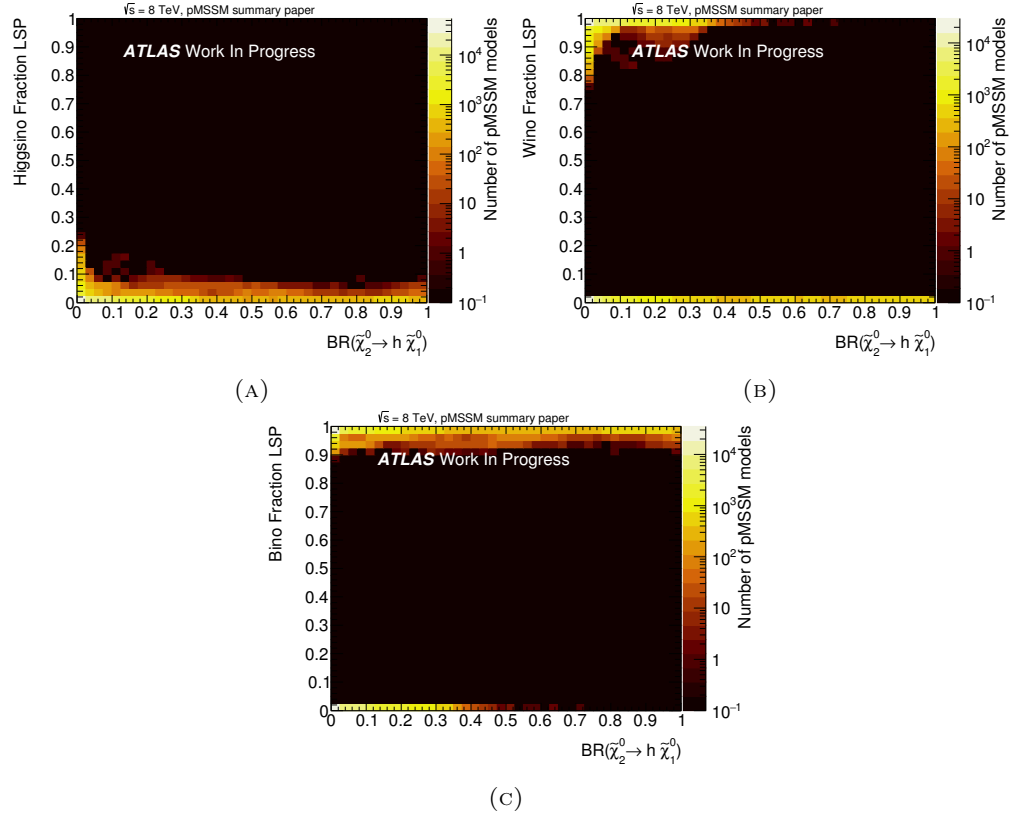


FIGURE 1.5: pMSSM models (post-Run 1 of the LHC) showing the (A) higgsino, (B) wino and the (C) bino fraction of the LSP as a function of the branching ratio of $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$.

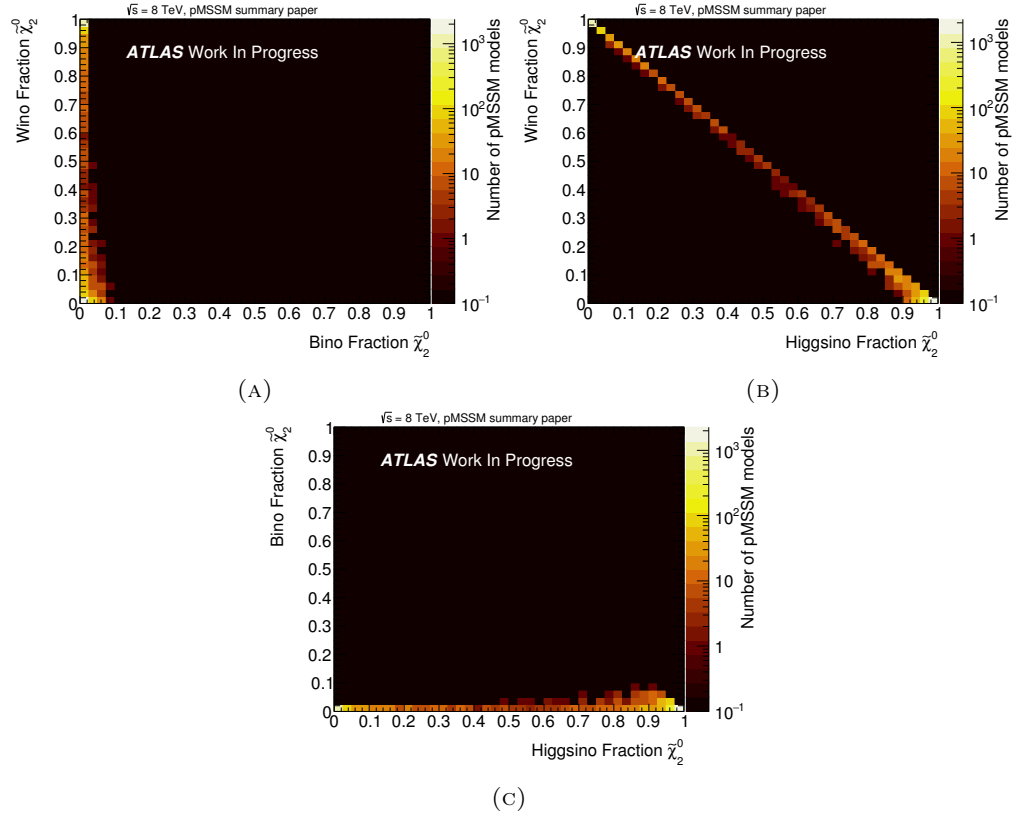


FIGURE 1.6: pMSSM models (post-Run 1 of the LHC) showing the (A) wino-bino, (B) wino-higgsino and the (C) bino-higgsino fraction of the $\tilde{\chi}_2^0$ $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) > 0.8$ is required.

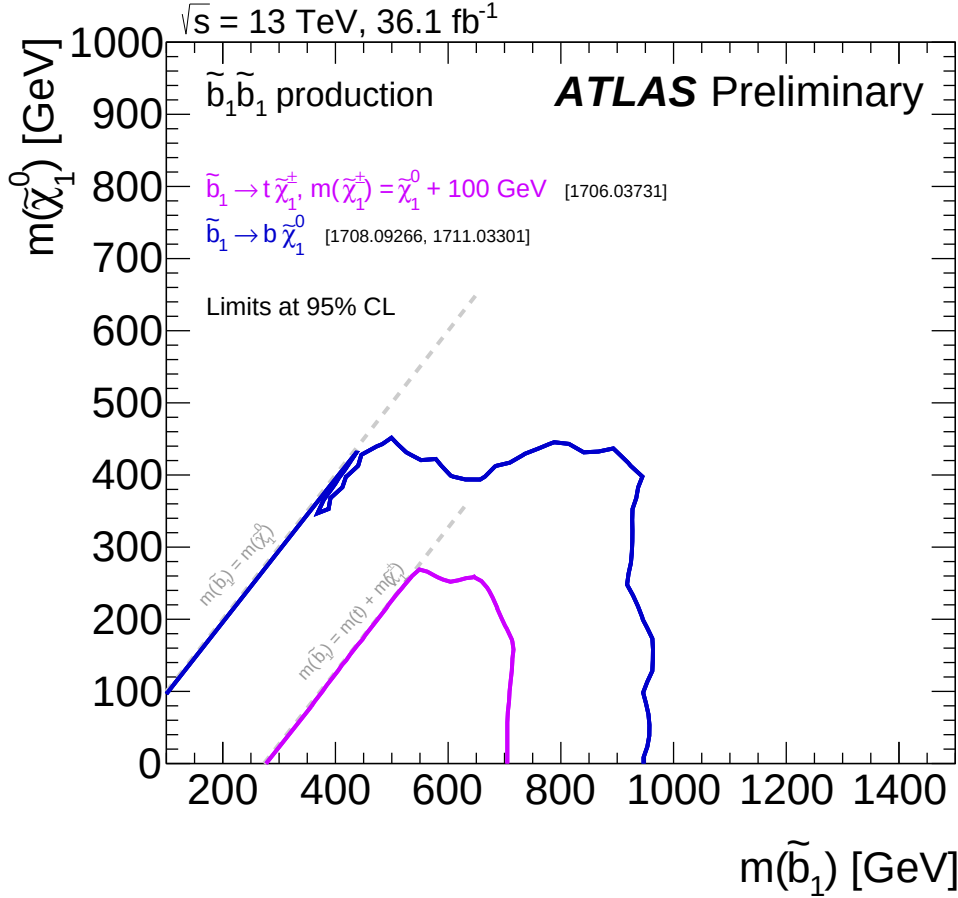


FIGURE 1.7: Exclusion limits at 95% Confidence Level in the $(\tilde{b}_1, \tilde{\chi}_1^0)$ mass plane for direct bottom-squark pair production presenting the results of different decay scenarios [75].

The dataset analysed corresponds to 36.1 fb^{-1} of proton-proton (pp) collision data at $\sqrt{s} = 13 \text{ TeV}$ collected by the ATLAS experiment during Run 2 of the LHC in 2015 and 2016. The analyses presented in the exclusion limit consider bottom-squarks decaying either directly to the LSP or through an intermediate stage involving the lightest chargino. The simplified models considered use either the following assumptions:

- Blue contour $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$ ($\mathcal{B} = 100\%$)
- Purple contour $\tilde{b}_1 \rightarrow t \tilde{\chi}_1^\pm$ ($\mathcal{B} = 100\%$)

The bottom-squark mass is excluded up to a maximum of approximately 950 GeV.

Bottom-squark searches performed prior to the presented analysis typically introduce fewer new particles within simpler decay chains than the targeted process. The advantage of considering a complicated process is that it produces a unique final state that is less likely to have been produced through known SM physics than the final states targeted by previous searches, presenting an opportunity to more effectively identify and reject events originating from SM processes.

Models with a bino-like $\tilde{\chi}_1^0$ and a non-compressed mass splitting of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0)$ are not particularly well excluded by previous bottom-squark searches. The longer decay chains add extra particles to the final state which are perhaps vetoed by previous scalar bottom searches.

Figure 1.8 shows a summary of all ATLAS searches for supersymmetry from Run 1 and Run 2 of the LHC. The results show the mass limits achieved for particular sparticles within the context of simplified models. The results are presented in regions combining similar analyses, from the top to bottom: inclusive searches of pair produced gluinos; third generation direct pair production; electroweak pair production (for example $p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$); long-lived particles and R-parity violating (RPV) scenarios.

The limits presented show extensive searches across a range of simplified models and sparticles at different experiments, however these by no means are representative of the full supersymmetric phase-space and are only applicable to the very specific simplified models in question. This therefore does not necessarily mean that the particles could not exist at energies lower than what has already been excluded, they merely may be lying in a different location of the vast phase-space. The search for supersymmetry is ongoing and dominates a significant proportion of the physics programme at the ATLAS experiment.

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} d\mathcal{L} [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{q}^0$	E_T^{miss} E_T^{miss} E_T^{miss}	$\bar{q} \quad [2 \times, 8 \times \text{Degen.}]$ $\bar{q} \quad [1 \times, 8 \times \text{Degen.}]$	$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{g} \quad 0.43 \quad 0.71$ $\tilde{g} \quad 1.55$	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\bar{\ell})\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{g} \quad 1.85$ $\tilde{g} \quad 2.0$	$m(\tilde{\chi}_1^0) < 800 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 50 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{g} \quad 1.2$ $\tilde{g} \quad 1.8$	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 200 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{g} \quad 0.98$ $\tilde{g} \quad 2.25$	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 300 \text{ GeV}$
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{g} \quad 1.25$ $\tilde{g} \quad 2.25$	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_1^0) = 300 \text{ GeV}$
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple Multiple	$\tilde{b}_1 \quad 0.9$ $\tilde{b}_1 \quad 0.59-0.82$ $\tilde{b}_1 \quad 0.7$	$m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1^0) = 1$ $m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1^0) = 0.5$ $m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(\tilde{b}_1^0) = 1$
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_2^0 \rightarrow b\bar{b}\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{b}_1 \quad 0.23-0.48$ $\tilde{b}_1 \quad 1.0$	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\bar{b}\tilde{\chi}_1^0 \text{ or } \tilde{\chi}_1^0\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 0.48-0.84$ $\tilde{t}_1 \quad 1.16$	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ $m(\tilde{t}_1) = 800 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \bar{t}\nu\tilde{\chi}_1^0, \tilde{t}_1 \rightarrow \tau\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{t}_1 \quad 0.85$ $\tilde{t}_1 \quad 0.46$ $\tilde{t}_1 \quad 0.43$	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{\nu}) \cdot m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ $m(\tilde{t}_1, \tilde{\tau}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\bar{c}\tilde{\chi}_1^0 / \tilde{c}\bar{c}, \tilde{c} \rightarrow c\bar{c}\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 0.32-0.88$	$m(\tilde{\chi}_1^0) = 180 \text{ GeV}$
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	E_T^{miss}	$\tilde{t}_2 \quad 0.6$	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{t}_2) \cdot m(\tilde{\chi}_1^0) = 10 \text{ GeV}$
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	E_T^{miss} E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \quad 0.17$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \quad 0.42$	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_2^0) = 0$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \quad 0.68$	$m(\tilde{\chi}_1^0) = 0$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \quad 1.0$	$m(\tilde{\chi}_1^0) = 0$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\nu$	E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \quad 0.76$	$m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$ $m(\tilde{\chi}_2^0) = 0, m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_1^0))$
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1\nu(\tau\nu), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\tau(\nu\bar{\nu})$	E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \quad 0.22$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \quad 0.7$	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, m(\tilde{\chi}_2^0) = 180 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 0$
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	E_T^{miss} E_T^{miss}	$\tilde{\ell} \quad 0.18$ $\tilde{\ell} \quad 0.29-0.88$	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$
Long-lived particles	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	E_T^{miss} E_T^{miss}	$\tilde{H} \quad 0.13-0.23$ $\tilde{H} \quad 0.3$	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}\tilde{\chi}_1^0 \quad 0.15$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}\tilde{\chi}_1^0 \quad 0.46$	Pure Wino Pure Higgsino
	Stable $\tilde{g}$ R-hadron	Multiple	$\tilde{g} \quad 2.0$ $\tilde{g} \quad 2.05 \quad 2.4$	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	$\tilde{g} \quad 1.9$ $\tilde{g} \quad 1.33$ $\tilde{g} \quad 1.3$ $\tilde{g} \quad 1.05$ $\tilde{g} \quad 1.05$ $\tilde{g} \quad 0.55$ $\tilde{g} \quad 0.61$ $\tilde{g} \quad 0.42$ $\tilde{g} \quad 0.4$ $\tilde{g} \quad 1.45$ $\tilde{g} \quad 1.6$	$\tilde{\chi}_{1,11}^0 < 0.11, \tilde{\chi}_{1,12}^{0,1,2} < 0.07$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ Large $\tilde{\chi}_{1,12}^0$ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$, bino-like $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$, bino-like $\text{BR}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\bar{q}) = 100\%, \cos\theta = 1$
	LFV $p\bar{p} \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu\tau/\mu\tau$	E_T^{miss}	$\tilde{\nu}_\tau \quad 3.2$	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_2^0 \rightarrow W\bar{W}Z/\ell\ell\nu\nu$	E_T^{miss}	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_2^0 \quad 1.9$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_2^0 \quad 1.3$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_2^0 \quad 1.9$ $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_2^0 \quad 2.0$	
RPV	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\bar{q}q$	E_T^{miss} 4 e, μ	$\tilde{g} \quad 1.05$ $\tilde{g} \quad 1.05$ $\tilde{g} \quad 0.55$ $\tilde{g} \quad 0.61$ $\tilde{g} \quad 0.42$ $\tilde{g} \quad 0.4$ $\tilde{g} \quad 1.45$ $\tilde{g} \quad 1.6$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 1.05$ $\tilde{t}_1 \quad 0.55$ $\tilde{t}_1 \quad 0.61$ $\tilde{t}_1 \quad 0.42$ $\tilde{t}_1 \quad 0.4$ $\tilde{t}_1 \quad 1.45$ $\tilde{t}_1 \quad 1.6$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 1.05$ $\tilde{t}_1 \quad 0.55$ $\tilde{t}_1 \quad 0.61$ $\tilde{t}_1 \quad 0.42$ $\tilde{t}_1 \quad 0.4$ $\tilde{t}_1 \quad 1.45$ $\tilde{t}_1 \quad 1.6$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 1.05$ $\tilde{t}_1 \quad 0.55$ $\tilde{t}_1 \quad 0.61$ $\tilde{t}_1 \quad 0.42$ $\tilde{t}_1 \quad 0.4$ $\tilde{t}_1 \quad 1.45$ $\tilde{t}_1 \quad 1.6$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 1.05$ $\tilde{t}_1 \quad 0.55$ $\tilde{t}_1 \quad 0.61$ $\tilde{t}_1 \quad 0.42$ $\tilde{t}_1 \quad 0.4$ $\tilde{t}_1 \quad 1.45$ $\tilde{t}_1 \quad 1.6$	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	E_T^{miss}	$\tilde{t}_1 \quad 1.05$ $\tilde{t}_1 \quad 0.55$ $\tilde{t}_1 \quad 0.61$ $\tilde{t}_1 \quad 0.42$ $\tilde{t}_1 \quad 0.4$ $\tilde{t}_1 \quad 1.45$ $\tilde{t}_1 \quad 1.6$	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

FIGURE 1.8: A representative selection of the available search results presenting the mass reach of ATLAS searches for supersymmetry. Taken from [75].

Chapter 2

The Large Hadron Collider and the ATLAS Experiment

Particle colliders represent a modern experimental apparatus which allows for the testing and further understanding of the fundamental interactions of nature. Colliders generally offer three directions when attempting to explore new phase-space or to make more accurate measurements: increase the collision energy, increase the intensity, or increase the precision. The Large Hadron Collider (LHC) [76] at the European Centre for Nuclear Research (CERN), near Geneva, Switzerland, is a hadron-hadron synchrotron collider that produces collisions at the highest centre-of-mass energy ($\sqrt{s}$) ever achieved. The LHC also operates at an unprecedented intensity, providing data for research into even the rarest of interactions. Since it collides hadrons with a varying momentum transfer between the partons during each collision, it provides an excellent opportunity as a discovery machine in order to search for new physics beyond the SM across a wide range of energies. This chapter provides a brief description of the LHC, including details of the full accelerator complex - from bottle to bang, and concludes with a detailed description of one of the main experiments at the LHC: the ATLAS detector [77–80], providing details on the major systems from which it is constructed.

2.1 The Large Hadron Collider

The LHC was built in the existing 26.7 km tunnel originally constructed for the LEP experiment [81] and is at a depth varying between 50 m and 175 m below the ground. The commissioning and construction of LHC concluded in 2009. The accelerator is designed to provide proton-proton (pp) collisions at a centre-of-mass energy of up to $\sqrt{s} = 14$ TeV, however it has also provided collisions at 7, 8, and 13 TeV. The LHC is also capable of providing lead ion (Pb-Pb) and p -Pb collisions, with Pb-Pb collisions at centre-of-mass energies of $\sqrt{s} = 2.76$ TeV and 5.02 TeV per nucleon and p -Pb collisions with 5.02 TeV centre-of-mass energy per nucleon. Throughout this thesis, only pp collisions are considered.

The LHC circulates two beams of proton bunches in opposite directions in separate beam pipes and collides them at a number of interaction points. The beam pipes are maintained at ultra-high vacuum ($\sim 10^{-9}$ mbar). There are 1232 dipole magnets responsible for the bending of the beams into their circular orbit, while the 392 quadrupole magnets focus the beams at the interaction points to ensure that the two beams collide. The dipole magnets provide a 8.4 T magnetic field

and is achieved using NbTi superconducting magnets cooled to approximately 1.9 K using liquid Helium as part of a complex cryogenic system.

Within the LHC, protons are accelerated using sixteen superconducting radio frequency (RF) cavities operating at a frequency of 40 MHz with an acceleration gradient of 16 MV/m. A continuous beam is not desirable or even possible at the LHC. Instead, the particles are grouped into bunches by the RF cavities. The LHC beams can accommodate $n_b = 2808$ bunches, where each bunch contains $N_p = 1.15 \cdot 10^{11}$ protons on average. The bunches are nominally separated by 25 ns, producing a collision rate of $f = 40$ MHz, however the machine can be operated with varying bunch spacings.

The LHC requires a very high intensity in order to observe rare processes such as the creation of the Higgs boson or signatures of new physics. To detect these events, fast response, finely segmented and radiation-hard detectors are needed. There are four main experiments, situated at each of the four interaction points along the LHC ring: ATLAS and CMS [82] are both general purpose detectors featuring extensive semiconductor based tracking systems, large coverage calorimeters and efficient muon detectors. They were designed to discover and measure the Higgs boson and for searches of physics beyond the SM, however they also pursue a considerable physics programme in precision measurements of the SM; ALICE (A Large Ion Collider Experiment) [83] is designed to study heavy-ion collisions, implementing a large Time Projection Chamber (TPC) along with complementary sub-detectors; LHCb [84] is constructed as a one-sided forward arm spectrometer in order to efficiently measure the decay products of B-hadrons, which are often expected to be produced in the forward region.

LHC Accelerator Complex and Performance

The accelerator complex at the LHC is composed of a succession of accelerators connected together, progressively increasing in size and designed to incrementally accelerate the particles until they are eventually injected into the final stage of the chain: the LHC. Figure 2.1 shows the full CERN accelerator complex. The protons begin as Hydrogen atoms, which are ionised and fed into the first accelerator, the LINAC-2, and accelerated to 50 MeV. They are then injected into the Proton Synchrotron Booster (PSB) and leave with an energy of 1.4 GeV to the Proton Synchrotron (PS). The proton beam is then accelerated up to 26 GeV in the PS and passed to the Super Proton Synchrotron (SPS) and increased in energy again up to 450 GeV. Finally, the proton bunches are then injected in both directions into the LHC, where they are accelerated to their final energy. The bunches are then compressed to a length corresponding to 1.71 ns (decreased further to 1.06 ns for collision), with a bunch spacing corresponding to 25 ns. The interaction rate is directly related to the size and frequency of the bunches as is described in Equation 2.3.

Run 1 of the LHC data taking began in March 2010 and ended early 2013, initially colliding beams with a centre-of-mass energy of $\sqrt{s} = 7$ TeV (2010-2011), which was then increased to 8 TeV (2012-2013). For a period of two years, a substantial campaign to upgrade the machine began and the LHC was restarted at the beginning of 2015. LHC Run 2 extended from 2015 until late 2018 and was operational at a centre-of-mass energy of $\sqrt{s} = 13$ TeV.

Besides from the beam energy, the key parameter of a collider is the luminosity that it is able to deliver. The instantaneous luminosity ($\mathcal{L}$) is a measure of the intensity of the collision rate and directly relates the event rate to the cross-section (σ) for a particular physics process:

$$\frac{dN}{dt} = \sigma \cdot \mathcal{L} \quad (2.1)$$

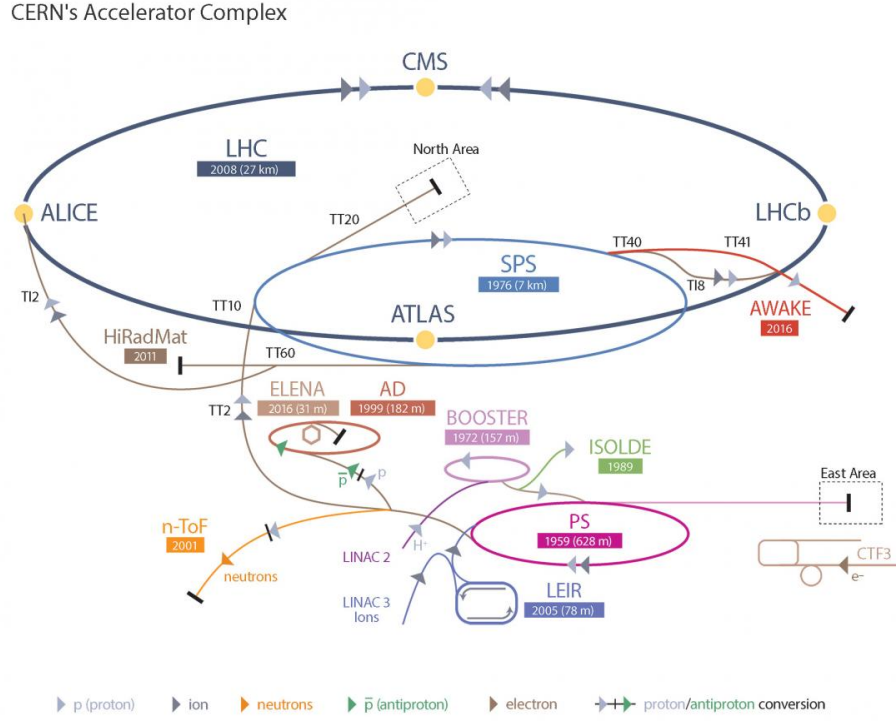


FIGURE 2.1: The CERN accelerator complex comprising of the multi-stage system of injectors that are used to increase the proton energy. A subset of the many experiments supported by these accelerators is also presented [97].

The total number of events N produced is then obtained by integrating Equation 2.1 with respect to time.

$$N = \sigma \cdot \int \mathcal{L} dt = \sigma \cdot L \quad (2.2)$$

where L is the integrated luminosity and is measured in inverse barns (b^{-1}).

The instantaneous luminosity can be calculated from measured parameters of the accelerator, given by:

$$\mathcal{L} = \frac{N_b^2 n_b f_r \gamma}{4\pi \epsilon_n \beta^*} F \quad (2.3)$$

with:

N_b	number of protons per bunch
n_b	number of bunches per proton beam
f_r	revolution frequency of LHC
γ	relativistic gamma-factor
ϵ_n	normalised transverse emittance
β^*	beta function value at the interaction point
F	geometric luminosity reduction factor

The number of protons per bunch is typically $1.15 \cdot 10^{11}$ and the LHC can circulate a maximum of 2808 bunches. The revolution frequency is approximately 11.2 kHz and is determined by the fixed circumference of the LHC ring and by the known velocity of the circulating protons. The relativistic gamma-factor accounts for the relativistic velocities at which the protons travel and is approximately equal to 7000. The normalised transverse beam emittance and the beta function are related to the size and shape of the beam at the interaction point. The geometric reduction factor accounts for the crossing angle at which the beams collide. Table 2.1 presents the various beam parameters during LHC Run 1 and Run 2 in comparison to the nominal design values.

Parameter	Symbol [Unit]	Design	Run 1	Run 2
Beam energy	[TeV]	7.0	4.0	6.5
Bunch spacing	[ns]	25	50	25
No. bunches	n_b	2808	1380	2556
Bunch population	N_b [$10^{11} p$]	1.15	1.6	1.4
Revolution frequency	f_r [kHz]	11.2	11.2	11.2
Normalised emittance	ϵ_n [μm]	3.75	2.0	2.2
Beta function	β^* [cm]	55	60	25
Crossing angle	θ_c [μrad]	285	290	260
Peak luminosity	$\mathcal{L}$ [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.0	0.7	2.0

TABLE 2.1: Beam parameters during Run 1 (2012) and Run 2 (2018) in comparison to the nominal design values [76].

In order to increase the rate of event production, the luminosity is set as high as possible by increasing the bunch population and decreasing the bunch spacing. This leads to multiple simultaneous inelastic proton-proton collisions during each bunch crossing in a phenomenon referred to as *pile-up*. Several interactions that take place within the same bunch crossing is referred to as in-time pile-up, requiring that the experiments are capable of identifying the primary interaction vertex associated to the interesting physics processes. Additionally, the decay products of collisions occurring from adjacent bunch crossings may overlap in slow detector components and readout electronics, referred to as out-of-time pile-up. The combination of these effects requires fast, highly segmented detectors offering unprecedented timing and spatial resolution that are capable of performing in a high-radiation environment. Pile-up represents the average number of interactions per bunch crossing $\langle\mu\rangle$ [85].

2.2 The ATLAS Detector

The ATLAS detector has a diameter of 25 m, a length of 46 m and weighs 7000 tons. It is a 4π detector that covers nearly all the solid angle with active instrumentation, aside from a small angular range close to the entry and exit point of the beam pipe. The apparatus is typical of collider experiments, offering concentric, complementary sub-systems intended to specialise in specific tasks. ATLAS follows a forward-backward symmetric cylindrical geometry and is constructed from a main barrel section and two enclosing end-caps at either end.

The high energy and luminosity delivered by the LHC ensures that collisions in the ATLAS detector are at a high interaction rate, producing a high radiation environment, particularly in

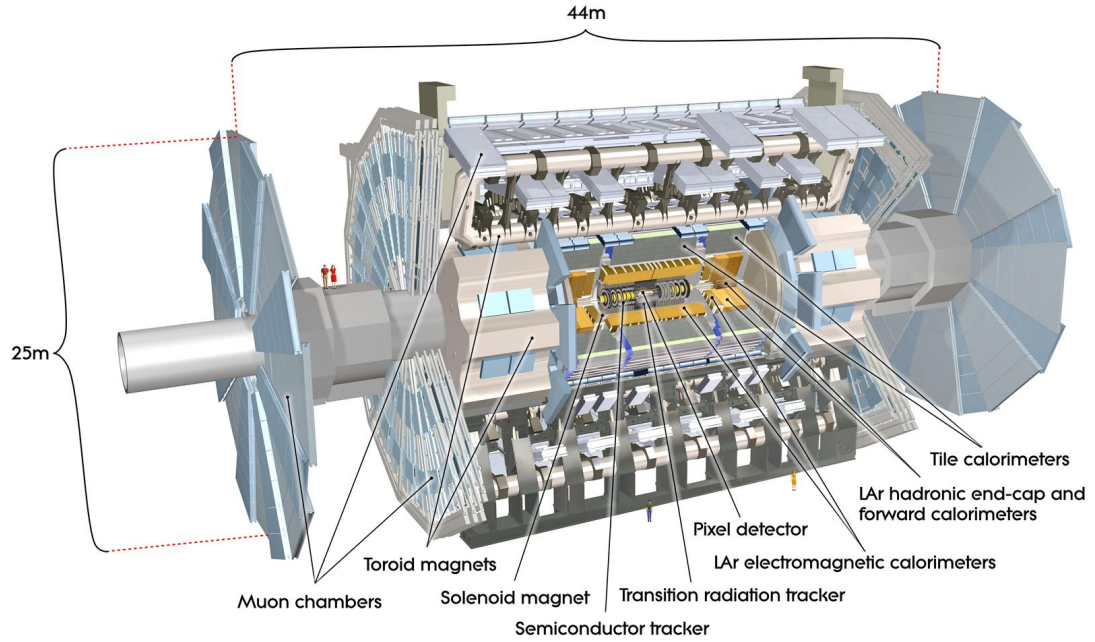


FIGURE 2.2: The ATLAS detector showing the concentric complementary sub-systems [77–80].

close proximity to the interaction point. The wide and varied physics programme imposes the following general requirements of the detector:

- Large geometrical acceptance with almost full azimuthal angle coverage.
- Good charged particle momentum resolution and reconstruction efficiency.
- High primary and secondary vertex reconstruction efficiency, allowing for identification of jets originating from b -quarks and τ leptons, requiring that a vertex detector is located close to the interaction point despite the very high radiation doses. Discussed in detail in Chapter 3.
- Electromagnetic and Hadronic calorimeters for the measurement and identification of electrons, photons and jets. These systems are also required to measure the total momentum in the transverse plane, allowing for calculation of the missing transverse momentum ($\mathbf{p}_T^{\text{miss}}$) in an event, as discussed in Chapter 3.
- Precise muon identification and momentum resolution across a wide range of momenta.
- Fast and flexible trigger system able to select events of interest through feature and particle identification; allowing for rejection of undesirable background events while functioning at a high readout rate.

ATLAS uses a right-handed Cartesian coordinate system (x, y, z) with the origin at the nominal interaction point and the z -axis parallel to the beam pipe. The x -axis points to the centre of the LHC ring, while the y -axis points vertically upwards. Polar coordinates (r, θ, ϕ) are preferable given the cylindrical design, where the azimuthal angle ϕ is defined around the beam axis in the x - y plane and ranges from $-\pi$ to π . This plane is also transverse to the beam pipe and offers a useful advantage in that conservation of momentum can be imposed on the system before and

after a collision. Instead of using the polar angle θ , it is convenient to use the pseudorapidity, defined as:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (2.4)$$

since the difference in pseudorapidity between two different particles is invariant under a Lorentz boost along the beam axis. Parallel to the beam axis $\eta = \infty$ and transverse to the beam, parallel to the y -axis, $\eta = 0$. The aforementioned barrel and end-cap sections are responsible for covering the range of $|\eta| < 1.4$ and $1.5 < |\eta| < 4.7$ respectively, producing a near-hermetic detection capability. The distance in the pseudorapidity-azimuthal angular region is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, and is commonly used when measuring the angular separation between particles.

The structure of the detector is divided into complementary sub-detectors forming a concentric cylindrical geometry, in which different particle types leave different unique signatures. Each sub-system utilises a different experimental detection technique in order to fulfil its purpose. The collective performance of the sub-systems allows for particle identification. The innermost section is the tracking system. In the highest radiation environment, charged particles are measured with high accuracy within a 2T solenoidal magnetic field, allowing for the measurement of the curvature of the particles path that is used to determine the transverse momentum. The tracking system is composed of semiconductor pixel and strip detectors that are surrounded on the outer layer by a straw-tube tracking detector capable of producing and detecting transition radiation. Collectively these detectors form the inner detector (ID). It was foreseen that the high radiation would degrade the pixel detector layers closest to the beam pipe, and hence for Run 2, an additional pixel layer was installed closest to the beam pipe and is known as the Insertable B-Layer (IBL) [86–88]. A detailed description of the ID is provided in Section 2.3.

The next sub-detector is the calorimetry system, which is composed of the Electromagnetic (ECAL) and the hadronic (HCAL) calorimeters and has a pseudorapidity coverage of $|\eta| < 4.9$. These detectors are designed to absorb and measure the energy of electromagnetically interacting and strongly interacting particles respectively. Both calorimeters are designed to fully contain the particles and the showers that they produce. More information on the calorimetry system is given in Section 2.4.

The outermost section of the ATLAS detector is the muon spectrometer. This consists of a large toroidal magnet system and muon trackers. The high magnetic field in use with the muon trackers provides tracking information and allows for momentum measurements of the incident muons. Muons are the only charged particles that can pass through the calorimeters without significantly interacting. Since muons only minimally interact with matter, this system is the largest volume sub-detector within ATLAS to increase probability of detection. A detailed description is provided in Section 2.5.

When considering the collision rate of protons within the LHC, the ATLAS detector is ingenious in managing the bandwidth and disc space capabilities in order to process and record desired physics events. The trigger system architecture relies on hardware and software stages in order to select the events of interest to collectively reduce the rate of events from 40 MHz down to a manageable rate in the order of 100 Hz. A detailed description is provided in Section 2.6.

2.3 Inner Detector

The ID is the subsystem that is situated closest to the interaction point and is composed of three independent yet complementary sub-detectors: the Pixel Detector, the Semi-Conductor Tracker and the Transition Radiation Tracker. The ID is positioned within a 2 T axial magnetic field along the beam axis that is produced by a thin superconducting solenoid magnet. A cross-sectional view of the ID is presented in Figure 2.3 and depicts the three sub-detectors and layer positions with respect to the beam pipe.

The ID is designed to provide pattern recognition in order to reconstruct tracking parameters with high resolution and to determine primary and secondary vertices with high precision. The trajectories of the incoming particles are reconstructed from the *hits* in the silicon pixel sensors and are referred to as *tracks*. The ID is also designed to measure the momentum of incident charged particles across a wide range of energies, where tracks can be reconstructed from particles with $p_T > 300$ MeV. An important tracking parameter is the *impact parameter*. This quantity is related to the measurement of secondary vertices and is a vital measurement in the identification of jets originating from heavy-flavoured quarks, such as those from b -quarks. The BSM physics search presented relies upon this experimental technique and is described in detail in Chapter 3.

Given its proximity to the interaction point, the ID is required to provide all of the aforementioned functionality within a very high radiation environment, and hence must be highly radiation tolerant.

The overall momentum measurement and resolution provided by the ID system is:

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% \cdot p_T \oplus 1\% \quad (2.5)$$

where the symbol $\oplus$ represents the sum in quadrature. Table 2.2 presents a summary of the intrinsic resolutions of the subsystems of the ID.

Detector Component	Sensor Element Size (μm)	Intrinsic Resolution (μm)
IBL	50×250	8×40
Pixel	50×400	10×115
SCT	80	17
TRT	4000	130

TABLE 2.2: An overview of the intrinsic resolutions of the ID components. The sensor element size corresponds to the active detector component of the sensor. The sensor element size and intrinsic resolution are given in terms of $(R - \phi, z)$ for the IBL and pixel detectors, and $(R - \phi)$ for the SCT and TRT. Taken from [98].

Pixel Detector

The Pixel Detector sub-system [89] is situated closest to the beam pipe, ranging from 33.25 mm to 122.5 mm. During Run 1, the pixel detector consisted of three cylindrical barrel layers radially located at 50.5, 88.5 and 122.5 mm, and of three discs on either side of the interaction point in the forward direction (z -axis) located at ± 495 , ± 580 and ± 650 mm, which ensure coverage in the high- η region. However, during the first long shutdown of the LHC, the ATLAS Pixel Detector was upgraded to include an additional innermost layer, IBL, which is now positioned

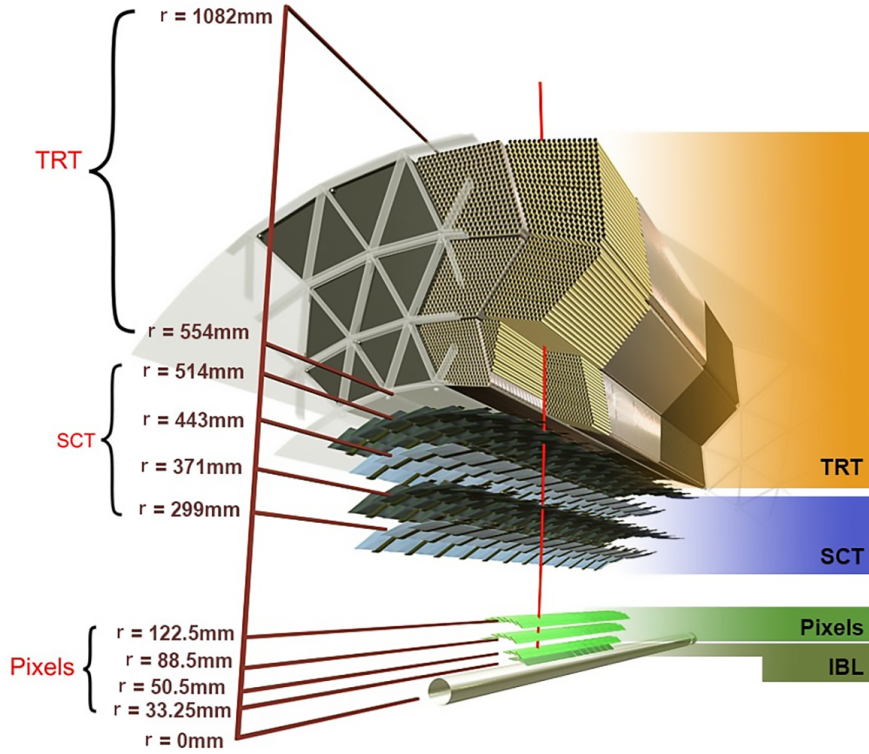


FIGURE 2.3: A schematic cross-section of the ID in the barrel section of the ATLAS detector, depicting the layers of the sub-systems and the distance at which they are located from the interaction point. Taken from [99].

at 33.25 mm. The Pixel Detector provides a fully hermetic detection surface in the azimuthal angle ϕ and a longitudinal coverage of $|\eta| < 3.0$.

The three outermost layers support 1744 silicon pixel modules, with dimensions of $19 \times 63 \text{ mm}^2$ and a thickness of $250 \mu\text{m}$. Each module contains 46080 readout channels, with these layers providing over 80.4 million readout channels in total. These layers produce an intrinsic spatial resolution of $10 \mu\text{m}$ in the R - ϕ plane orthogonal to the beam axis, and $115 \mu\text{m}$ in the z -axis. The pixel sensors utilised in these three outer layers are a type of *hybrid* pixel sensor referred to as *planar*. In hybrid assemblies the charge is generated in a dedicated silicon sensor, where the signal is further processed and readout by a separate chip. The readout chip used in the three outermost layers is the FE-I3 and is coupled to the sensor via a metallic bump bonding. The combined sensor and readout chips are referred to as a *module*. Planar sensors are a common technology in large surface tracking detectors since they are highly radiation tolerant while providing a fast readout.

The IBL is the innermost layer that was inserted in 2015 and consists of fourteen carbon-fibre support structures, known as *staves*, each loaded with twenty pixel modules. The addition of an extra layer situated closer to the beam pipe improves the quality of impact parameter reconstruction for tracks, and hence improves heavy-flavour tagging performance. The sensors are of two types: planar and 3D sensors [90]. A total of twelve double-chip planar n-in-n sensors populate the central barrel section. Each planar sensor is bump-bonded to two FE-I4B readout chips [91], which are responsible for the processing and readout of the analogue signal. The ends of the staves are populated with 3D sensors. These sensors feature electrodes that extend into the silicon bulk and are hence known as 3D sensors. The staves are mounted to accommodate a 14° rotation with respect to the radial direction in order to ensure overlap of the active area. Both the planar and 3D sensors have a pixel size of $250 \times 50 \mu\text{m}^2$ and are positioned such that the

shorter pixel direction is in the R - ϕ plane in order to maximise the impact parameter resolution in the transverse plane.

Each stave also provides the electrical and cooling services required for operation. Radiation damage typically increases the leakage current of the sensors, which in turn dissipates power causing the sensor to heat. This increase in temperature further increases the leakage current due to thermal excitation of the electron-hole pairs. To avoid this effect, a dedicated cooling system is deployed to remove excess heat from each module, which can typically reach approximately 4 W [89].

Semi-Conductor Tracker

Surrounding the Pixel Detector is the Semi-Conductor Tracker (SCT), a silicon strip detector designed to provide eight precision measurements per track in the intermediate radial range, contributing to the measurement of momentum, impact parameters and vertex position. The barrel section is composed of four layers of silicon micro-strip modules covering the pseudorapidity range $|\eta| < 1.4$ and nine end-cap discs on either side covering $1.4 < |\eta| < 2.5$. Each module consists of two strip layers with a mean strip pitch of $80\ \mu\text{m}$. The detection principle is the same as for the Pixel Detector, however it encompasses long strips of silicon rather than the pixelated structure since the particle density at the given radial distance is significantly reduced. The SCT is made up of 4088 modules with approximately 6.3 million readout channels. The intrinsic resolution of the SCT is $17\ \mu\text{m}$ in the R - ϕ plane and $580\ \mu\text{m}$ in the z -axis.

Transition Radiation Tracker

The outermost sub-system of the ID is the Transition Radiation Tracker (TRT). The detection principle is based on the collection of photons emitted when a charged particle traverses between regions of differing dielectric constants. The intensity of the transition radiation is proportional to the Lorentz factor $\gamma = E/m$. Since electrons have a low mass when compared to heavier particles, such as hadrons, the intensity of the transition radiation is used for particle identification and in particular to discriminate between pions and electrons. The TRT consists of straw drift tubes with a diameter of 4 mm and provides coverage up to $|\eta| = 2.0$. In the central region, the straw tubes are parallel to the beam axis and are 144 cm in length. In the end-cap region, the 37 cm-long straws are arranged radially in wheels. The straw tubes are filled with a Xe-based gas mixture and are interleaved with polypropylene fibres (barrel) or foils (end-caps), which serves as the transition radiation material. The TRT provides R - ϕ information for the determination of the transverse momentum with an accuracy of $130\ \mu\text{m}$. The TRT is expected to receive a large number of hits, typically 36 per track. This high number of hits and the larger track length compensate for the lower spatial resolution of each hit in comparison to the silicon detectors.

2.4 Calorimeter Systems

Continuing radially outwards from the ID is the next major system of the ATLAS detector: the calorimetry systems. Figure 2.4 depicts the various components of the calorimetry system [92]. The calorimeters are responsible for measuring the energies of incident particles (except muons and neutrinos) and are composed of alternating layers of passive and active material. As an incident particle traverses the material, it interacts with the passive material and creates cascades of particles in a process referred to as *showering*. The deposited energy of these showers, also known as *clusters*, is then absorbed and measured in the active layers and allows for the inference of the total energy of the initial particle [92]. The magnet system that surrounds the ID is

designed to minimise the amount of material in front of the calorimeter in order to reduce energy loss.

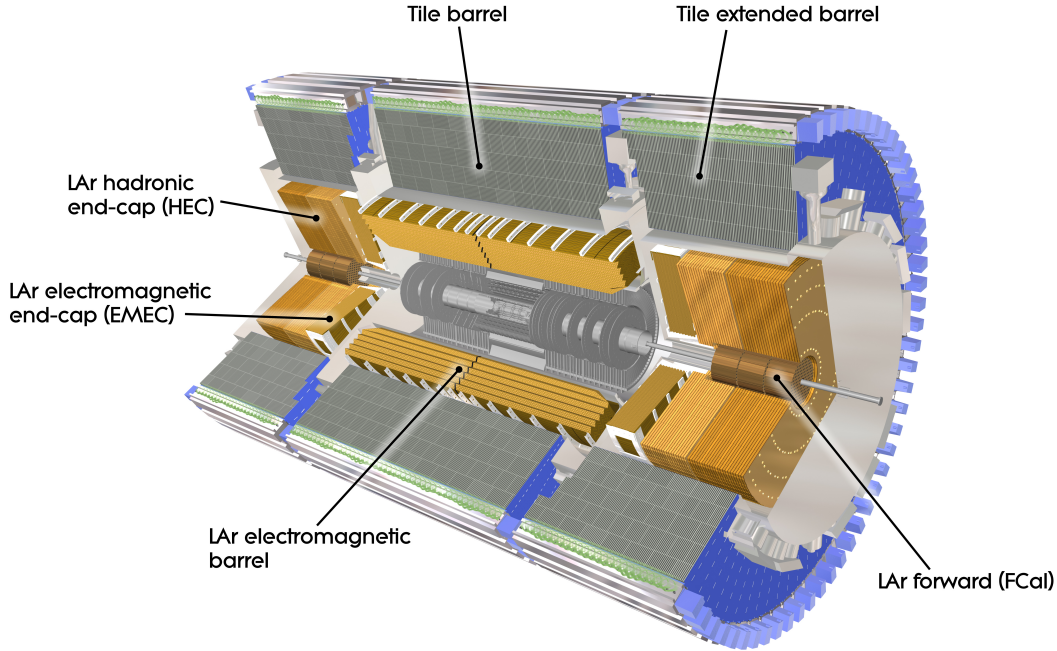


FIGURE 2.4: Overall layout of the ATLAS calorimetry system. Taken from [77].

There are two calorimeter systems used in the ATLAS detector: the Electromagnetic calorimeter and the Hadronic calorimeter, and are based on different technologies. The Electromagnetic calorimeter is positioned after the ID with the Hadronic calorimeter following in close succession. They are dedicated to measuring the energies of electromagnetically interacting and strongly interacting particles respectively. The Electromagnetic calorimeter is composed of three main sections: the barrel and two end-caps, where they are composed exclusively of lead-LAr (liquid argon) calorimeters. The Hadronic calorimeter follows a similar structure, with a barrel section and two end-caps, however the barrel section, also referred to as the tile calorimeter, consists of steel as the absorber material and scintillators as the active medium. The end-caps of the Hadronic calorimeter are based on lead-LAr calorimeters. In order to correct for the energy losses of particles when passing through inactive material in the ID and in the calorimeters, a presampler is positioned immediately in front of the Electromagnetic calorimeter. The presampler accounts for any initial energy loss and is used to correct the total energy within the shower. Forward calorimeters are positioned in the very forward region, in order to provide coverage in $3.1 < |\eta| < 4.9$.

In the Electromagnetic calorimeter, electrons and positrons radiate photons via bremsstrahlung, which in turn produces electrons and positrons through pair production. These two processes alternate, producing a shower of particles that interact with the material via ionisation. Photons are also detected in this way, following similar decay processes beginning with pair production and subsequent bremsstrahlung processes. Ionisation electrons are produced by the passage of charged particles through the material. These electrons then drift to electrodes and are collected, where the magnitude of the current is proportional to the energy of the initial particle. The energy of the initial particle decreases exponentially with $E(x) = E_0 e^{-x/X_0}$. The parameter X_0 is called the *radiation length*, which is material-dependent and is defined as the mean distance over which the energy of the particle is reduced by a factor of $1/e$.

In the Hadronic calorimeter, the hadronic showering process is dominated by a succession of inelastic hadronic interactions via the strong force. Hadronic showers typically deposit a non-negligible amount of energy in the Electromagnetic calorimeter prior to the Hadronic calorimeter, which is mainly caused by the decay of the pion $\pi^0 \rightarrow \gamma\gamma$. An analogous quantity to the radiation length for the Hadronic calorimeters is the *interaction length*, λ .

Both the Electromagnetic and Hadronic calorimeters are designed to fully contain the shower of the incident particle, where hadronic showers are typically longer and hence the Hadronic calorimeter is positioned further away from the interaction point than the Electromagnetic calorimeter. The Electromagnetic calorimeter is designed to be around $22 X_0$ in length, while the Hadronic calorimeter is more than 10λ in length, ensuring accurate measurements of particle energies and the missing transverse energy. The combined calorimeter systems provides a coverage of $|\eta| < 4.9$.

The relative energy resolution of each calorimeter can then be parametrised in the following way:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (2.6)$$

where a represents the stochastic contribution from the intrinsic fluctuations of the number and energy of particles produced within the shower; b represents the effect of noise originating from pile-up and from the readout electronics; and c is due to systematic effects such as mis-calibration of the detector as well as accounting for the inactive material present in the detector [93]. At low energy the uncertainty is driven by the high pile-up levels, whereas at high energies the systematic effects become dominant. Table 2.3 shows the energy resolution of the different calorimeters, presenting the sampling term (a) and the constant term (c).

Detector Component	Energy Resolution ($\sigma(E)/E$)	Eta Coverage
Electromagnetic Calorimeter	$10\%/\sqrt{E} \oplus 0.17\%$	$ \eta < 3.2$
Hadronic Calorimeter Barrel	$50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$
Hadronic Calorimeter End-cap	$50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$
Forward Calorimeter	$100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$

TABLE 2.3: Energy resolutions of the constituent calorimeter sections. Taken from [92].

Electromagnetic Calorimeters

The Electromagnetic calorimeters consist of lead absorbers, which follow an accordion-shape (depicted in Figure 2.5(a)); liquid argon as the active medium; and collection electrodes, responsible for the measurement of the deposited energy. This accordion geometry provides complete and uniform coverage in the azimuthal angle ϕ . The thickness of the absorber plates is designed to vary with η in such a way so as to provide optimal energy resolution throughout [92]. In the barrel, the accordion waves are parallel to the beam axis, where the folding angle changes with the radius in order to maintain a constant liquid argon spacing. In the end-caps, the accordion waves run axially and the folding angle varies with the radius. The barrel calorimeter is positioned in a cryostat that also contains the inner solenoid. The end-caps are also located inside a cryostat.

The barrel section of the calorimeter is longitudinally separated into three layers. Prior to the three layers is the presampler, an 11 mm-thick layer of liquid argon. Figure 2.5(b) shows the three

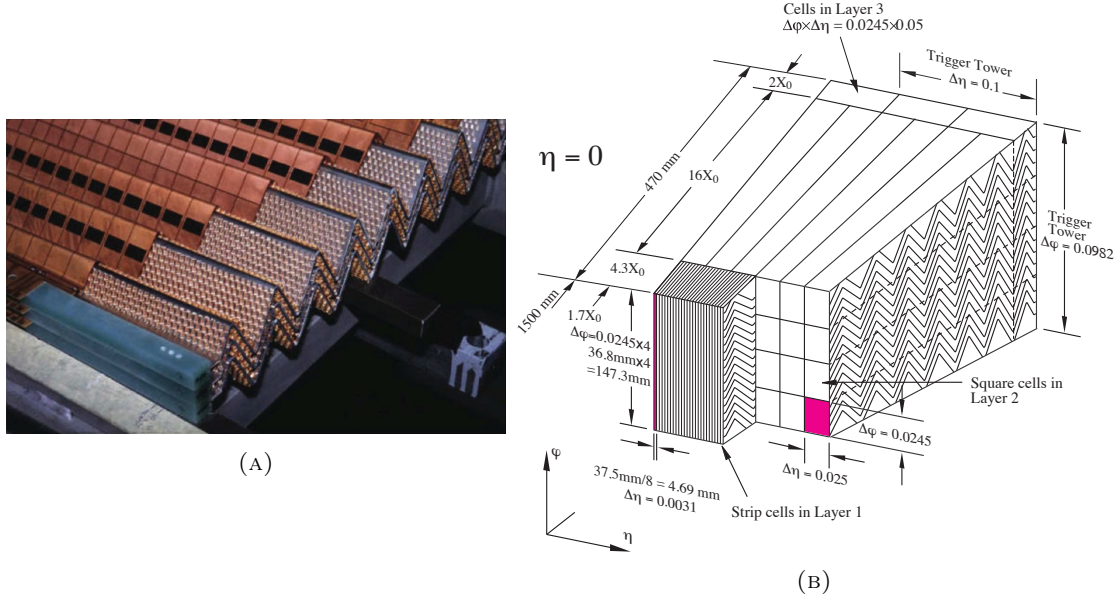


FIGURE 2.5: (A) Accordion-shaped geometry of the LAr calorimeter. (B) A schematic of the barrel Electromagnetic calorimeter. The three layers of the calorimeter and the accordion layout of the lead absorbers and electrodes are shown. Taken from [77].

layers and the accordion geometry of a single module of the Electromagnetic barrel calorimeter. The first layer has a granularity of 0.0031×0.0982 in $\eta \times \phi$. The cells are also referred to as strips due to their fine segmentation in η . The first layer provides the ability to distinguish between particles with minimum spatial separation and hence allows for excellent identification between photon pairs originating from pions, from individual photons. The second layer has a more coarse granularity of 0.025×0.0245 in $\eta \times \phi$. It has a thickness equivalent to 16 radiation lengths and is thus intended to measure the majority of the energy deposition. The third layer offers even coarser granularity, where the purpose is to correct for the overlap of the energy deposition in the subsequent Hadronic calorimeter. The total depth of the Electromagnetic calorimeter exceeds 22 radiation lengths in the barrel section and 24 in the end-caps.

The barrel section of the Electromagnetic calorimeter consists of two identical half-barrels, separated by a gap of 4 mm at $z = 0$. Each half barrel is composed of 16 individual modules, each covering $\Delta\phi = 22.5^\circ$, consisting of 1024 accordion shaped lead absorbers interleaved with the readout electrodes. The readout electrodes consist of three conductive copper layers that are separated by insulating kapton tape. The two outer layers are at high voltage, whereas the middle layer is for the readout of the signal via capacitive coupling. As ionisation electrons are produced by an incident charged particle, they drift in the electric field and are collected in order to infer the energy of the incident particle. The lead absorbers have a thickness of 1.53 mm (1.13 mm) in the range $|\eta| < 0.8$ ($|\eta| > 0.8$). The size of the drift gap is 2.1 mm. The total coverage provided by the barrel calorimeter is $|\eta| < 1.475$. Including the presampler cells, a barrel module features 3424 readout cells.

The end-cap calorimeters are composed of two coaxial wheels: an outer wheel and an inner wheel, covering the range $1.375 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$ respectively. These wheels are further divided into eight wedge-shaped modules, where the outer wheel consists of 768 absorbers interleaved with readout electronics and the inner wheel of 256. The absorbers have a thickness of 1.7 mm for $|\eta| < 2.5$ and 2.2 mm for $|\eta| > 2.5$. A module in the end-cap consists of approximately 4000 readout cells.

Hadronic Calorimeters

The Hadronic calorimeter exploits two different technologies: liquid argon calorimeters in the end-caps (as in the Electromagnetic calorimeter) and scintillator-tile detectors in the barrel section. In the central section of the barrel, referred to as the Tile Barrel ($|\eta| < 1.0$), and the Tile Extended Barrel ($0.8 < |\eta| < 1.7$), plastic scintillator tile detectors are used, utilising steel as the absorbing material because of its high density. The barrel and extended barrels are divided azimuthally into 64 modules, where the layout is depicted in Figure 2.6. The tile calorimeter is divided into three layers, which are approximately 1.5, 4.1 and 1.8 interaction lengths in the barrel section and 1.5, 2.6 and 3.3 for the extended barrel. The total interaction length is approximately 10λ at $|\eta| = 0$. The tile calorimeter has a coarse granularity, with cells of $0.1 \times \pi/32$ for the first layer in $\eta \times \phi$. The sides of the scintillating tiles are readout by wavelength-shifting fibres into two separate photomultiplier tubes.

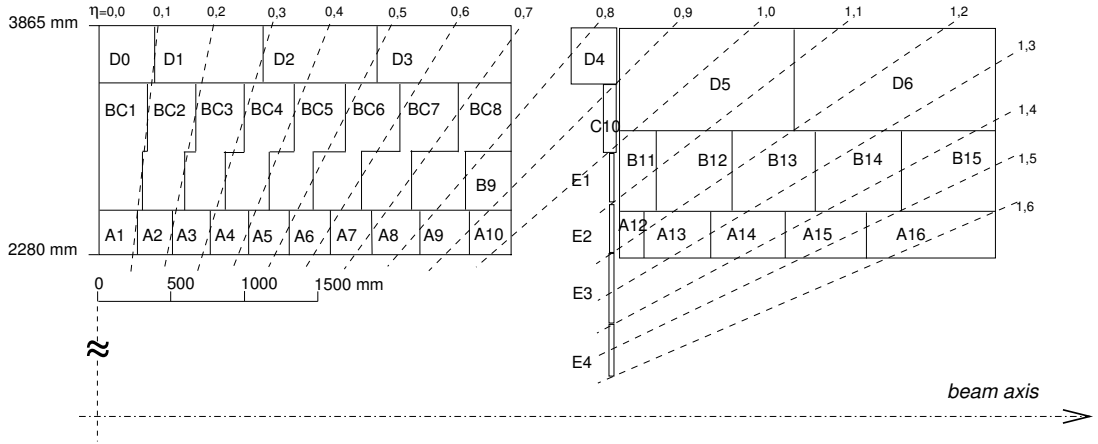


FIGURE 2.6: Segmentation in radial depth and pseudorapidity of the tile-calorimeter modules in the central (left) and extended (right) barrels. The bottom of the picture corresponds to the inner radius of the tile calorimeter and is parallel to the beam pipe. The tile calorimeter is symmetric about the interaction point at the origin. Taken from [77].

The end-cap regions utilise a liquid argon calorimeter, where the active medium is liquid argon, however the absorber material is copper instead of lead. It is positioned behind the Electromagnetic end-cap and uses the same cryostats for the cooling of the liquid argon. The end-caps provide a coverage of $1.5 < |\eta| < 3.2$.

Forward Calorimeters

The forward calorimeters are high density liquid argon calorimeters in the far forward regions of the detector. They provide coverage from $3.1 < |\eta| < 4.9$. Each forward calorimeter is split into three layers. The first layer consists of copper absorbers in order to provide electromagnetic measurements, while the remaining layers utilise tungsten absorbers. The total depth of the forward calorimeter is equivalent to approximately 10λ .

Figure 2.7 shows a the cumulative depth of material in terms of the interaction length as a function of the pseudorapidity throughout the various layers of the detector. The total is at least 10λ across all pseudorapidity regions, where the variations are caused by the transitions between the constituent components of the detector.

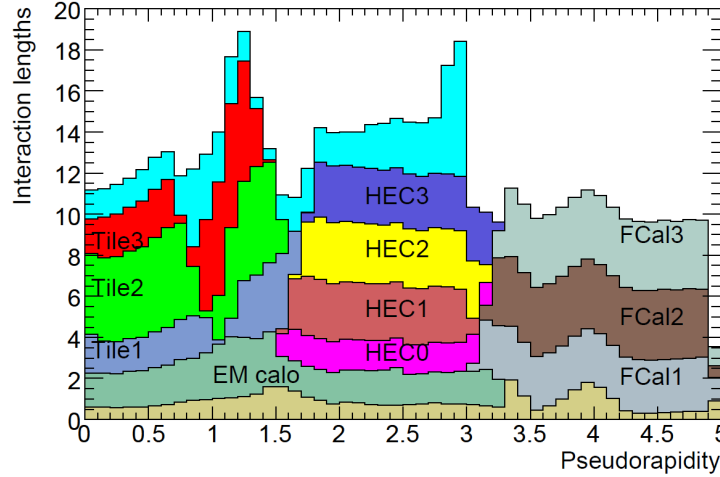


FIGURE 2.7: Cumulative depth of material in terms of the interaction length as a function of the pseudorapidity throughout the various layers of the detector. The schematic depicts the material in front of the Electromagnetic calorimeter (beige), the different layers of the Electromagnetic and Hadronic calorimeters, including the forward components, and finally the total amount of material in front of the first active layer of the muon spectrometer (light blue) up to $|\eta| < 3.0$. Taken from [77].

2.5 Muon Spectrometer

Surrounding the calorimeter system, and making up the final detector system of ATLAS, is the muon spectrometer, presented in Figure 2.8. It is designed to detect and measure the momentum of charged particles that are not already stopped by the calorimeters, namely muons. The muon spectrometer is required to perform two functions: high precision tracking, and triggering. The muon sub-system consists of four detector technologies. The Monitored Drift Tubes (MDTs) and Cathode Strip Chambers (CSCs) are responsible for the precision tracking in the barrel region and end-caps respectively, collectively covering the region $|\eta| < 2.7$. The Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) are used as triggering chambers in the barrel region and end-caps respectively, and provide trigger capability in the region $|\eta| < 2.4$.

The MDT consists of three concentric cylindrical layers that run perpendicular to the beam-pipe and are responsible for the precise determination of the muon track in the bending plane, $|\eta|$. The second and third layers provide a coverage of $|\eta| < 2.7$, whereas the first layer provides a coverage of $|\eta| < 2.0$. There are 1088 chambers, which provide a total active area of 5500 m^2 . The MDT chambers consist of three to eight layers of drift tubes that are capable of achieving an average resolution of $80 \mu\text{m}$ per tube and $35 \mu\text{m}$ per chamber.

The CSC chambers are the innermost layer and are constructed from multi-wire proportional chambers with cathode planes divided into strips in orthogonal directions. The CSC is implemented in two discs per end-cap, which are segmented into eight chambers each. Each chamber consists of four planes that allows for four measurements of η and ϕ for each muon track. The ϕ coordinate is measured by the time the induced charges take to drift to the collection cathode. The spatial resolution provided by a CSC chamber is $40 \mu\text{m}$ in the bending plane and approximately 5 mm in the transverse plane. The CSC layers collectively provide a coverage of $2.0 < |\eta| < 2.7$.

Especially designed chambers are used to trigger on muons. These muon trigger chambers are capable of providing signals approximately $15\text{--}25 \text{ ns}$ after the traversing of a charged particle and thus allow for identification of a particular bunch crossing, making them suitable for triggering.

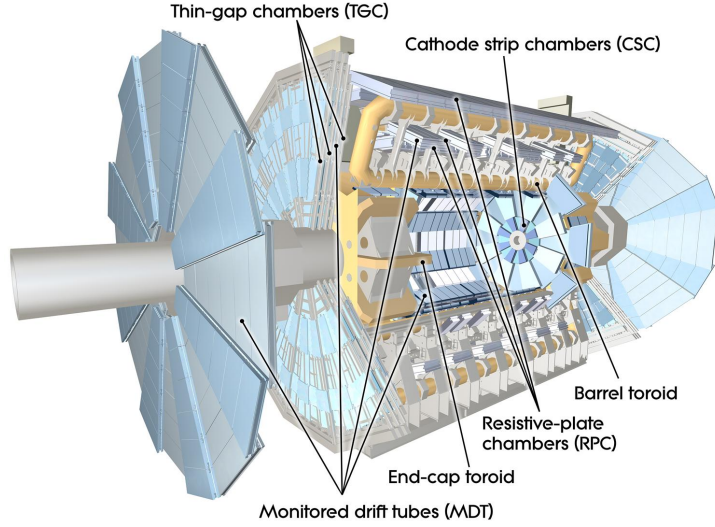


FIGURE 2.8: A general overview of the ATLAS muon detectors and their location within the detector. Taken from [77].

They are designed to measure both the η and ϕ coordinates of the track, where the ϕ coordinate information is complementary to the information from the chambers used for precision tracking. The RPCs are used in the barrel region ($|\eta| < 1.05$) and provide a spatial resolution of approximately 10 mm in both the bending ($|\eta|$) and non-bending (ϕ) planes. The end-caps use TGCs in the region $1.05 < |\eta| < 2.4$ and provide spatial resolutions of 2-7 mm in the bending plane (η) and 3-7 mm in the non-bending plane (ϕ) [94].

The measurement of the momentum of muons is based on the magnetic deflection of their tracks within the magnetic field provided by the ATLAS toroidal magnet system, presented in Figure 2.9. The toroidal magnet system is composed of three air-core toroidal magnets: one in the barrel region and two end-cap magnets, and measures 26 m in length and 20 m in diameter. Each of the toroids is composed of eight coils that are positioned radially around the beam-pipe and are symmetrical in order to provide a homogenous field. The barrel toroid provides a magnetic field of approximately 0.5 T in the range $|\eta| < 1.4$. The two end-cap toroids provide a magnetic field of approximately 1 T in the range $1.6 < |\eta| < 2.7$.

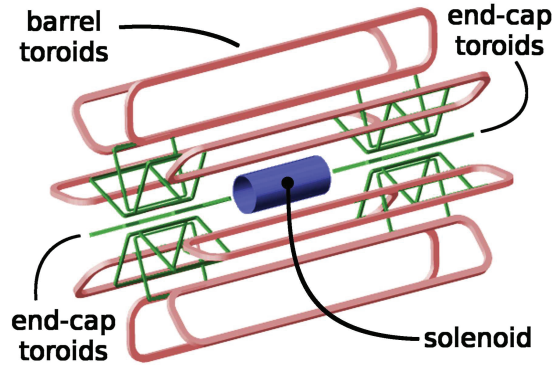


FIGURE 2.9: A schematic view of the magnet systems of the ATLAS detector. Taken from [100].

The precision tracking chambers achieve a muon momentum resolution of $\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV. The momentum resolution also benefits from the air-core structure of the toroid magnets since it reduces the effects of multiple-scattering [95].

2.6 Trigger and Data Acquisition

The ATLAS trigger and data acquisition system (TDAQ), diagrammatically presented in Figure 2.10, is responsible for the selection of physics events in the ATLAS detector. The dominant process that occurs in the proton collisions is inelastic scattering. The searched-for processes by ATLAS are significantly rarer and hence a dedicated system is implemented to reject the majority of events that are uninteresting, while selecting the rarer, interesting physics processes. A multi-level trigger system is implemented, consisting of the Level 1 hardware trigger (L1) and a High Level software trigger (HLT), where the requirements of both triggers must be satisfied in order to accept an event and write to disc.

The L1 trigger is designed to have access to data directly from the calorimeters and the muon spectrometer. Information with a reduced granularity with respect to nominal is used to identify electrons, photons, tau-leptons and jets, as well as transverse energy and missing transverse energy. Requirements on various kinematic and phenomenological features of the incident particles must be met in order for it to be identified. The muon spectrometer provides fast trigger signals that are used for the L1 trigger decision. The maximum L1 trigger rate is 100 kHz, where each event is on average 1.3 MB in size.

An event selected by the L1 trigger is then processed by the HLT, a software-based trigger system. The HLT is designed to perform a more complete examination of the event, where it performs a global track reconstruction and receives tracking information from the ID, as well as from the calorimeters and the muon spectrometer. This additional information allows for trigger selections on particles identified by the ID, such as jets originating from b -quarks. Within one second, the HLT selects approximately 1500 events that are collected into an event record and distributed to the offline storage facilities whereby a complete off-line reconstruction can be performed [96].

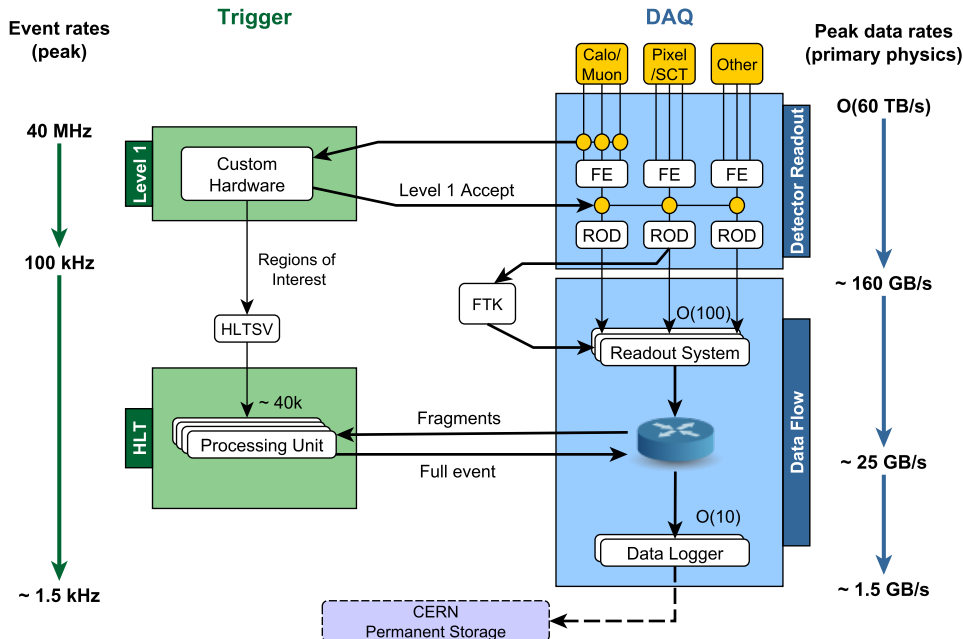


FIGURE 2.10: Schematic diagram of the ATLAS Trigger and Data Acquisition system. Also presented are expected peak rates and bandwidths for each component. Taken from [101].

2.7 ATLAS Datasets

The data-taking of the ATLAS detector can be divided into two main periods of operation: Run 1 - between 2010 and early 2013, and Run 2 - between 2015 and 2018, where the Long Shutdown I separated the two data-taking periods and was used as a time to upgrade the detector. The total luminosity that the LHC delivered during Run 1 was ~ 5.5 (22.8) fb^{-1} during 2011 (2012) at $\sqrt{s} = 7$ (8) TeV respectively. During Run 2, the LHC provided 156fb^{-1} of proton-proton collisions at $\sqrt{s} = 13 \text{TeV}$, of which 147fb^{-1} was recorded by the ATLAS detector. Of the total recorded, 95% is deemed to be of high enough quality for physics analyses, representing a total of 139fb^{-1} . The BSM search presented in Chapter 4 utilises the full Run 2 data-set of 139fb^{-1} .

Figure 2.11 depicts the annual delivered luminosity, where each year of data-taking is presented. The total amount of delivered luminosity increases with each year of data-taking. Figure 2.12 depicts the cumulative luminosity delivered by the LHC during Run 2, the total recorded by the ATLAS detector and the total deemed to be of high enough quality for physics analyses. Figure 2.13 shows the average number of interactions per crossing, μ , referred to as pile-up. The differences between the data-taking years is caused by the differences in LHC machine parameters during operation. The average pile-up for Run 2 was found to be $\langle \mu \rangle = 33.7$.

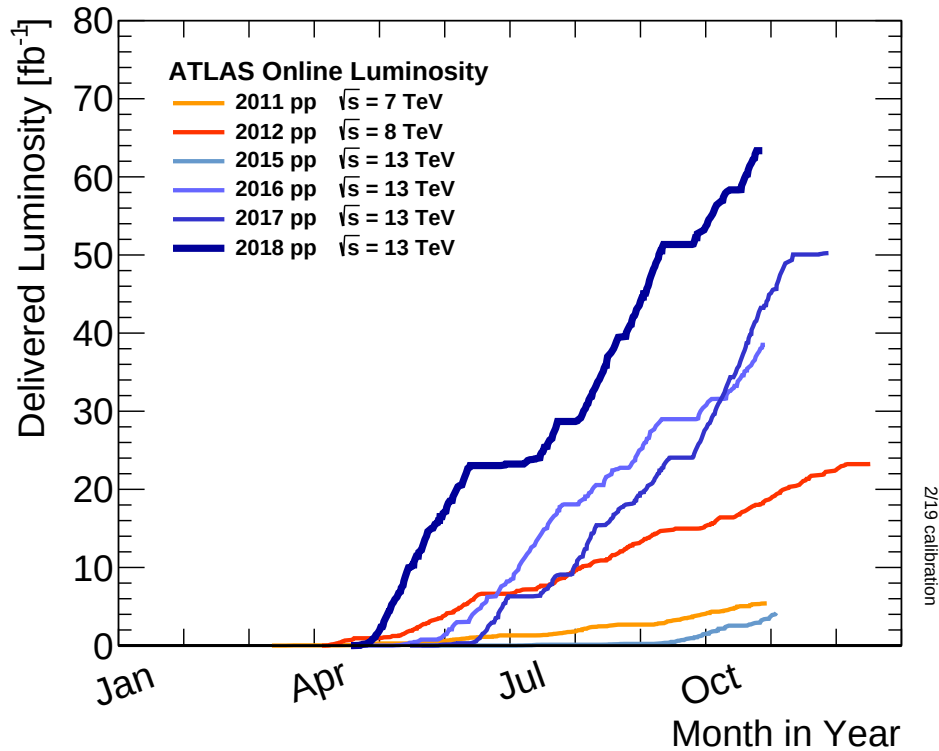


FIGURE 2.11: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy pp collisions. Taken from [102].

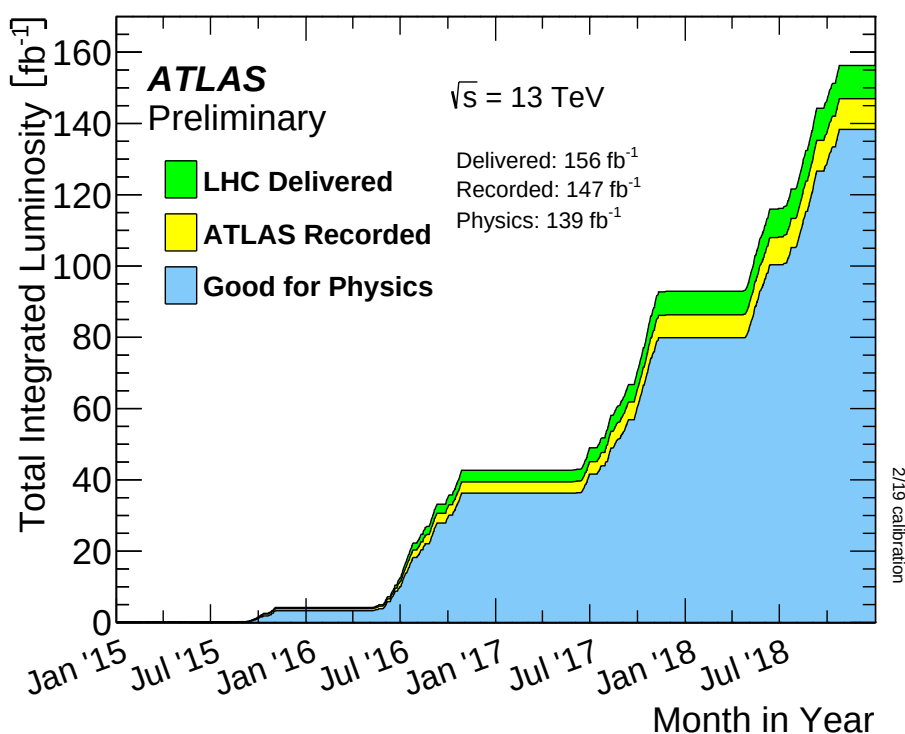


FIGURE 2.12: Cumulative luminosity versus time delivered to the ATLAS detector (green), the cumulative luminosity recorded by ATLAS (yellow), and the data certified to be of good enough quality for data analysis (blue) during stable beams for pp collisions at 13 TeV centre-of-mass energy in 2015-2018. Taken from [102].

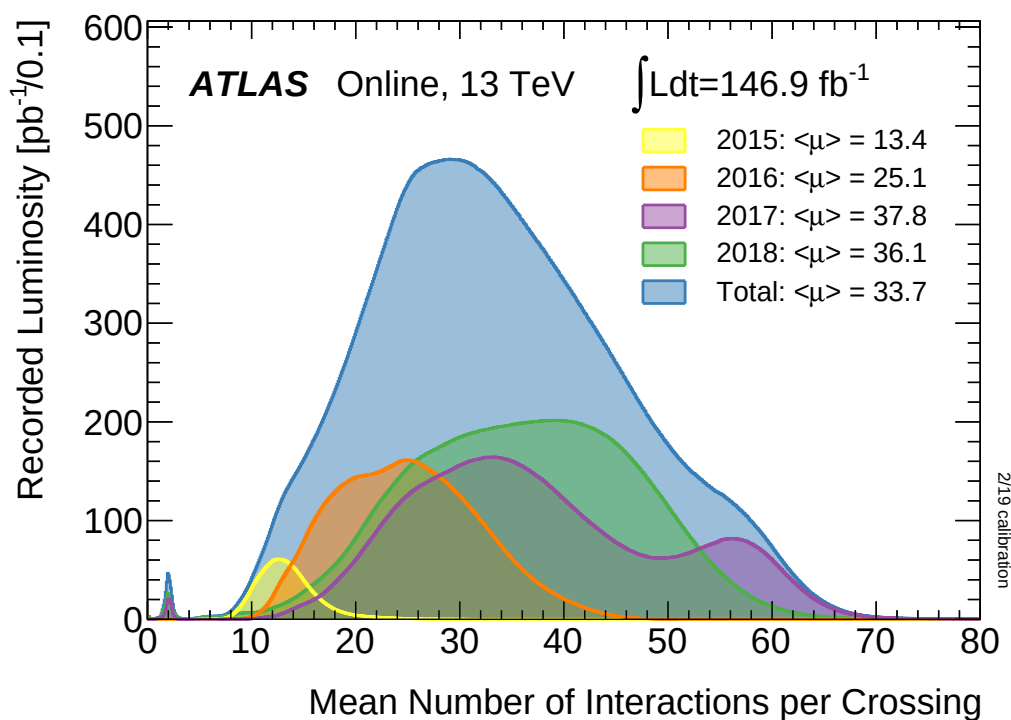


FIGURE 2.13: Luminosity-weighted distribution of the mean number of interactions per crossing for the pp collision data from 2015 to 2018 at $\sqrt{s} = 13 \text{ TeV}$ centre-of-mass energy. Taken from [102].

Chapter 3

Particle Identification with ATLAS Detector

The ATLAS detector is composed of several, complementary sub-systems, which are arranged in concentric, cylindrical sections and are collectively used to identify commonly produced stable particles during proton collisions. To allow for analysis of these collisions, the measured electrical signals have to be processed, grouped and combined such that they can be interpreted as the trace of a physical particle. This procedure is known as reconstruction. Each successive layer of the detector allows for recognition and discrimination between particles that can be reconstructed to form the event. Given the differences between the properties of particles, such as electric charge, the interactions that occur produce a unique signature and allows for particle recognition. Figure 3.1 depicts the most commonly produced particles and how they interact with the different detection layers as they traverse the detector. The signatures left in the detector allow for direct identification of particles (electrons, photons, muons and taus), reconstruction of a physical process attributed to particular particles (jets) or the inference of particles that do not interact with the detector and are only identifiable through the apparent energy imbalance in the transverse plane of the detector (E_T^{miss}). This chapter aims to introduce the reconstruction technique of the most important particles that are exploited in the BSM physics search detailed in chapter 4.

As charged particles traverse the detector, they are initially bent by the magnetic field, leaving hits in the ID. The reconstruction of these hits forms a track and is represented in Figure 3.1 with a solid line. The Electromagnetic calorimeter stops photons and electrons, depositing clusters of energy proportional to the energy of the incident particle. As photons traverse the ID, they can occasionally convert into an electron-positron pair and hence leave only a small number of hits and are referred to as conversion photons. Photons therefore leave an energy deposit in the Electromagnetic calorimeter that does not correspond to an associated track. Electrically neutral particles, such as the photon, are represented by dashed lines. Hadrons continue through the Electromagnetic calorimeter and deposit their energy in the Hadronic calorimeter. Muons, being electrically charged, leave a track, however deposit only a small amount of energy in the calorimeters and travel through to the muon spectrometer. Within the volume of the muon spectrometer, their path is bent by a magnetic field and are measured before they escape the detector. Particles such as the neutrino can traverse the entire detector without interacting at all. The presence of these particles can only be realised by imposing the conservation of energy and deducing the missing energy and hence direction.

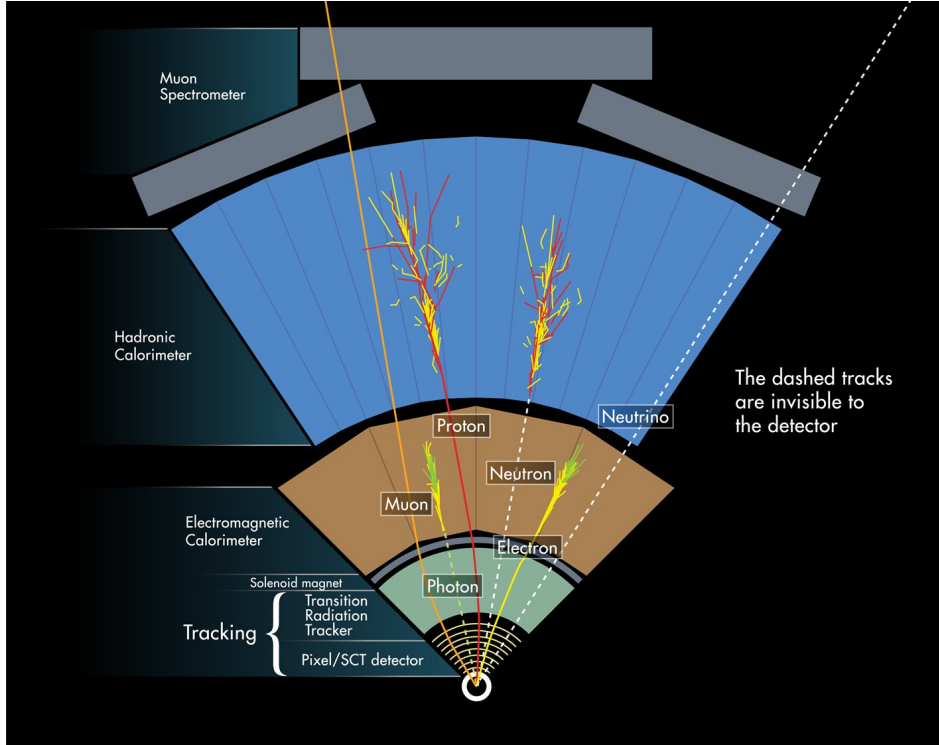


FIGURE 3.1: A representation depicting how commonly produced particles interact with the various sub-detectors of the ATLAS detector, allowing for particle identification. Taken from [136].

3.1 Track and Vertex Reconstruction

Charged particle tracks are reconstructed in the ID using a sequence of algorithms and requires a minimum number of hits within the silicon layers to be used as seeds, while additional points can be added to extend the track [103].

Initially, hits in the pixel detector and SCT are constructed into three-dimensional space points. The SCT requires a hit on both sides of the module in order to measure both coordinates. The hits in the TRT are constructed into drift circles by using the timing information. A seed is formed from the constructed space points of the pixel detector and the first SCT layer. This track is extended to the fourth layer of the SCT using a Kalman-filter [104]. This track candidate is then extended by fitting to the TRT hits. This procedure is intended to reconstruct tracks originating from prompt particles¹.

Secondly, an algorithm begins with the remaining hits in the TRT that have not yet been assigned to a track. It then extends the track inwards by adding points from the SCT and pixel detector layers. This additional procedure is effective at reconstructing tracks from conversion photons or from long-lived particles that do not necessarily leave a hit in the innermost layers of the detector. The effects of pile-up and instrumental inefficiencies can cause the appearance of ‘fake’ tracks, and are reduced by requiring a hit in either the IBL or the innermost pixel layer and rejecting tracks where an expected intermediate hit cannot be identified [103]. Tracks are only considered if $p_T > 500$ MeV and $|\eta| < 2.5$. The track reconstruction efficiency for $p_T < 5$ GeV achieves between 85-90% [105].

¹Prompt particles are defined as particles which originate from the initial pp interaction with a lifetime greater than $3 \cdot 10^{-11}$ s or from the subsequent decay or interaction of such particles with a lifetime less than $3 \cdot 10^{-11}$ s.

Vertex candidates are then found using finder algorithms that assign the tracks to a vertex. A reconstructed vertex is required to have at least two tracks associated to it, while the primary vertex is defined as the vertex with the largest $\sum p_T^2$ of all tracks. Secondary vertices and conversion photons are then reconstructed from additional, dedicated algorithms. The vertex reconstruction efficiency is inversely proportional to the pile-up, however achieves an approximate 90% efficiency for vertices with at least two associated tracks [106, 107].

Important quantities associated to track reconstruction are the transverse and longitudinal impact parameters. The transverse impact parameter (d_0) is defined as the distance of closest approach in the $R - \phi$ plane of the track to the primary vertex, while the longitudinal impact parameter ($z_0 \sin \theta$) is defined as the distance of the track to the primary vertex in the longitudinal plane at the point of closest approach in $R - \phi$ plane [108]. These quantities are of fundamental importance in the identification of jets originating from b -quark fragmentation.

3.2 Electrons and Photons

Electrons and photons deposit all of their energy in the Electromagnetic calorimeter, such that no energy deposition is expected in the Hadronic calorimeter. In contrast to photons, electrons, being charged particles, leave tracks in the ID and can therefore be distinguished. However, since the shower process of electrons and photons is similar, separating the signatures between electrons and conversion photons is not straightforward.

The reconstruction begins with energy deposits in the cells of the Electromagnetic calorimeter. A tower of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ measures the total transverse energy, defined as the sum of the energy deposited in the longitudinal layers within all cells of the tower. An algorithm is then designed to group several calorimeter cells together in order to form a cluster, using towers that measure a total transverse energy $E_T > 2.5$ GeV as seeds for the process. This ‘pre-cluster’ and information from the ID are used to reconstruct the final Electromagnetic cluster.

If a high-quality track, identified to originate from the primary vertex, can be extrapolated to align with the cluster in the Electromagnetic calorimeter, then the particle can be identified to be an electron. In the absence of such a matched track, the particle is identified to be an unconverted photon. If a matching track is found that originates from a conversion vertex, then the particle is identified as a converted photon. Additional information from the TRT allows for rejection of signatures originating from pions or jets that appear to be an electron.

The energy of the particle is estimated from the constructed cluster in the calorimeter and from properties of the track and depends on the pseudo-rapidity of the particle, while accounting for corrections factors from simulation. Additionally, the abundance of $Z \rightarrow e^+e^-$ events are used to calculate calibration factors [109–111].

Differing identification working points are defined from *loose* to *tight*, with increasing background rejection and decreasing signal efficiency. These definitions are dependent on the fraction of energy deposited in the Electromagnetic calorimeter, the length and shape of the shower, the quality of the matched track and the requirements for correct matching between track and cluster. Particles are also required to meet an isolation requirement, ensuring that the energy cluster and tracks are well-defined [112, 113]. A similar strategy is utilised for photons [114, 115].

3.3 Muons

The reconstruction of muons relies on information from the ID and the muon spectrometer, which is complemented by information from the calorimeters in the region $|\eta| \sim 0$, where there is a small region uncovered by the muon spectrometer [116, 117]. Track segments are initially constructed in the muon spectrometer and are then combined to form a complete track. Tracks identified in the ID are combined with the tracks in the muon spectrometer and can form different muon candidates: combined muons use track information from both the ID and the muon spectrometer and segment-tagged muons are constructed from track information from the ID which can be extrapolated to the muon spectrometer and correctly matched with an energy deposit within at least one of the segments. Combined muons provide the best muon tagging method, where the reconstruction efficiency reaches close to 99% in the central region of the detector.

Differing identification working points are defined from *loose* to *tight*, with increasing background rejection and decreasing signal efficiency. These definitions are dependent on the quality of the tracks in the ID and the muon spectrometer and how successfully the tracking information matches [116, 117].

3.4 Jets

Particles that carry a QCD colour charge can only exist in colour-neutral hadrons, as introduced in Section 1.2. Therefore, the quarks and gluons produced in the hard parton scattering process during proton collisions undergo hadronisation. The top quark, comparatively much heavier than the other quarks, is an exception and decays before hadronisation can occur. The quarks and gluons produced form a spray of colour-neutral hadrons in the direction of travel of the initial particle. The abundance and momentum of these hadrons is indicative of the energy of the initial parton. This collimated flow of particles is known as a jet. Hadronic jets are the most commonly produced object during proton collisions and are the experimental signature of the production of a quark or gluon. Hence, in order to recover the information about the initial quark or gluon, the ATLAS experiment uses a dedicated algorithm used to reconstruct the collimated hadrons produced during hadronisation.

The majority of their energy is deposited in the Hadronic calorimeter. Clusters are constructed from topological connected energy deposits in the calorimeters and are referred to as ‘topo-clusters’. These clusters are constructed from neighbouring calorimeters cells that detect an energy greater than a given threshold, reducing the noise from simulated pile-up and intrinsic electronic noise. Jets potentially originating from pile-up events are identified and rejected using jet vertex fraction (JVF), pseudorapidity selections and a minimum jet p_T . The JVF algorithm is designed to associate calorimeter clusters with tracks within the ID and assign a weight that is dependent on how likely the jet is to have originated from the primary vertex. This weight is calculated using information regarding the momentum fraction of the tracks associated with the primary vertex [118, 119]. These energy clusters are then used as inputs for a jet finding algorithm.

The algorithm that is used is called the anti- k_t sequential recombination algorithm [120]. This algorithm is widely used by ATLAS since it is less susceptible to the underlying activity in the event and to pile-up [121]. Sequential recombination algorithms attempt to minimise the distance (ΔR) between hadrons. The algorithm initially iterates over all clusters and finds the pair most closely separated and combines them to form a single cluster, utilising a p_T -weighted distance parameter d_{ij} . The iteration continues until all clusters in the event are separated by a distance greater than the defined jet radius parameter R . The radius parameter is chosen such that the

entire flow of hadrons is contained in the jet, while reducing the acceptance of underlying activity in the event. Typically, $R = 0.4$ is chosen for small jets and $R = 1.0$ or 1.2 for large jets. The analysis presented uses the anti- k_t algorithm with a radius parameter of $R = 0.4$.

The steps of the anti- k_t algorithm proceed as follows:

1. Introduce distances d_{ij} between clusters i and j , and d_{iB} between clusters i and the beam (B).
2. If the smallest distance is d_{ij} , then the two clusters are combined.
3. If the smallest distance is d_{iB} , then i is considered a jet and is removed.
4. The calculation of the distances is repeated until no clusters are left.

The distances are defined as:

$$d_{ij} = \min(p_{Ti}^{2p}, p_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad (3.1)$$

$$d_{iB} = p_{Ti}^{2p} \quad (3.2)$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$. R , y_i and ϕ_i are respectively the radius parameter, rapidity and azimuthal angle of particle i . The parameter p is equal to -1 for the anti- k_t algorithm and implies that the jet reconstruction proceeds from the hardest to the softest clusters.

This jet algorithm is not susceptible to *infra-red* and *collinear* effects in the hadronisation process. Infra-red safety implies that the jet clustering results are unaffected by an additional soft gluon, while collinear safety ensures the results are unaffected if one parton splits into two partons [122]. The top two illustrations of Figure 3.2 show how two jets can be incorrectly reconstructed as a single jet if a soft particle is radiated in-between the jets. The bottom illustrations show the effect of a particle within the jet splitting and how the reconstruction may not encompass all of the jet constituents.

The jets defined by the anti- k_t algorithm use hadronic clusters that are calibrated to the electromagnetic energy scale, the energy scale at which electromagnetic showers are correctly measured. Thus, a jet calibration is performed in order to account for the differences between an electromagnetic and hadronic shower. After the jets are reconstructed from the clusters, a correction and calibration is applied to the jet energy scale (JES) following the Global Sequential Calibration (GSC) and EM+JES scheme in order to correct for the mismeasurement of the reconstructed energy from the calorimeter compared to the true jet energy based upon the p_T and η of the jet. This correction implements various steps to account for detector response and performance [123].

The energy estimated to originate from pile-up is initially removed and the jet is required to have originated from the reconstructed primary vertex. The jet energy response is determined by:

$$\mathcal{R} = \left\langle \frac{E_{reco}^{MC}}{E_{truth}^{MC}} \right\rangle \quad (3.3)$$

Which is then inverted and applied as a correction factor. This factor compares the reconstructed (*reco*) energy to the true (*truth*) energy. A final calibration is calculated using in-situ measurements and is applied only to jets in data [124–127].

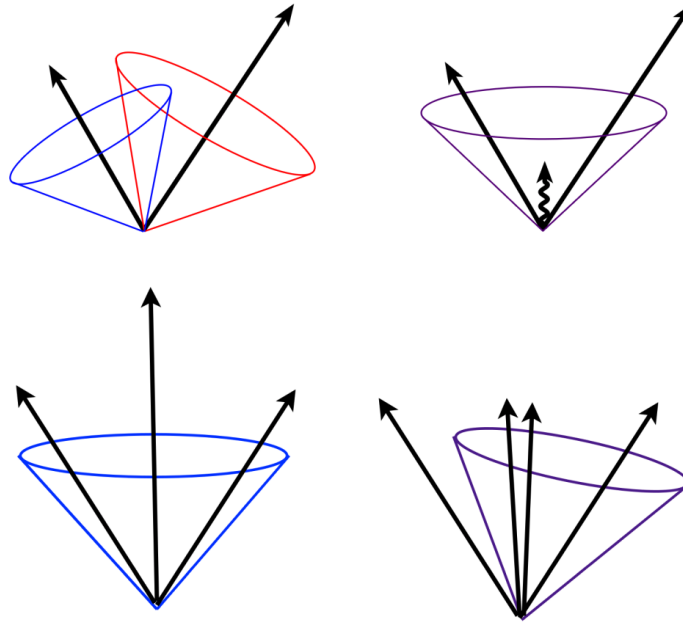


FIGURE 3.2: Illustration of the infra-red and collinear sensitivity of a jet reconstruction algorithm. Top: Infra-red, additional soft gluon affects reconstruction. Bottom: Collinear, a collinear splitting alters the number of jets. Taken from [122].

It is possible that jets can originate from sources other than the pp collision, such as proton interactions with the residual gas inside the beam pipe, or with material outside of the ATLAS detector e.g. the collimators. These jets are considered to be background, with cosmic muons and calorimeter noise also contributing. As a consequence, jets are subject to a jet cleaning selection before analysis, typically encompassing criteria based on the quality of the energy reconstruction, the jet energy deposits in the direction of the shower development and reconstructed tracks matched to the jets [128].

3.5 b -jets

The identification of jets originating from b -quark fragmentation (b -tagging) is of crucial importance to the physics activity at the ATLAS experiment. It is an essential experimental technique required for many physics analyses expecting b -quarks in the final state, including studies of the top quark, given its large decay rate to b -quarks; studies of the Yukawa coupling of the Higgs boson to the heaviest quarks: the top- and bottom-quark; and many BSM physics searches, including searches for supersymmetry. These differing analyses all require highly efficient algorithms capable of identifying the presence of b -hadrons in a highly dense environment over a broad range of particle momenta and pseudo-rapidities. b -tagging poses one of the greatest challenges of modern tracking detectors given the complex reconstruction environment. The BSM physics search presented in Chapter 4 relies significantly on the ability to identify jets to have originated from b -quarks.

When a b -quark is produced during a collision, it hadronises and produces a jet, referred to as a b -jet. The b -tagging method exploits properties of the b -hadron decay, utilising the reconstructed tracks within the ID that are associated to the b -jet. Hadrons containing b -quarks have a relatively long lifetime and given the high energies of the collision, they are able to travel a distance in the detector before producing a *secondary vertex*, marking the location of the b -hadron

decay. This is depicted in Figure 3.3, showing the production of a secondary vertex from the decay of a b -hadron within the jet. The dashed lines representing the transverse and longitudinal components of the momentum vector between the primary vertex and the secondary vertex are the impact parameters. The line labelled ‘Track Impact Parameter’ represents the transverse impact parameter. The average distance travelled by a b -hadron (with $p_T \simeq 50$ GeV) can be approximately calculated using the average lifetime ($\tau_b = 1.5 \cdot 10^{-12}$ s) as $d = \gamma\beta c\tau \simeq 3$ mm, where the relativistic boost $\gamma\beta \simeq 6$.

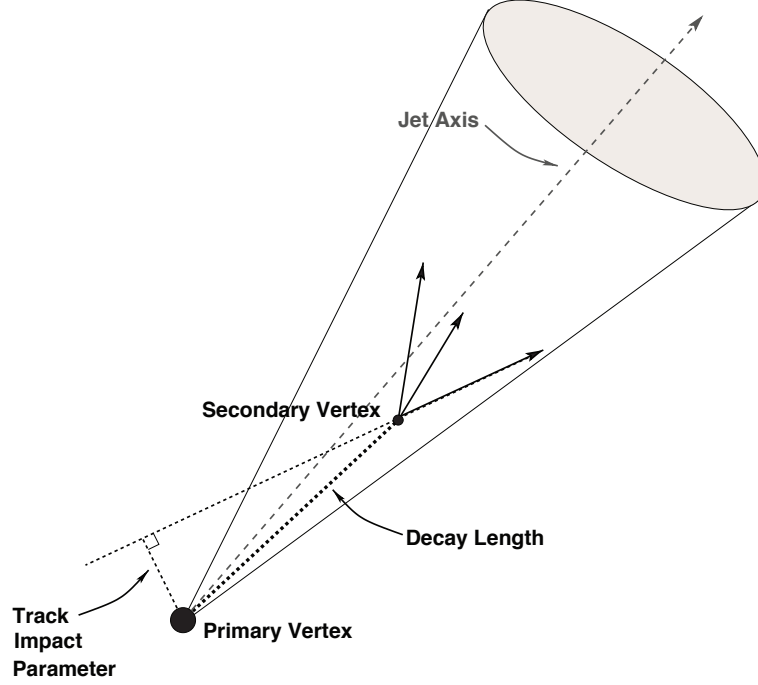


FIGURE 3.3: A diagram depicting the production of a secondary vertex from the decay of a b -hadron. Taken from [137].

Information from the transverse and longitudinal impact parameters can be used to distinguish between jets as b -jets, c -jets and light-jets². The strategy is based upon three distinct b -tagging algorithms: an impact-parameter based algorithm (IP3D), an inclusive secondary vertex reconstruction algorithm (SV1) and a decay chain multi-vertex reconstruction algorithm (JetFitter) [129]. These complementary b -tagging algorithms utilise information from the impact parameter, the secondary vertex and the full decay chain. A brief overview of the algorithms are described in the following:

- The **IP3D** algorithm utilises the transverse and longitudinal impact parameter. The corresponding significance is calculated for the transverse and longitudinal component as d_0 / σ_{d_0} and z_0 / σ_{z_0} respectively. Probability density functions are defined to discriminate b -jets from the light-jet hypotheses and are combined in a log likelihood ratio (LLR).
- **SV1** is designed to reconstruct a single secondary vertex in the jet using displaced tracks that do not originate from a long-lived particle or interaction with the detector material. The algorithm reconstructs an inclusive vertex with minimal assumptions on the number of tracks involved in the decay. It is based on a likelihood ratio formalism similar to that used for IP3D algorithm.

²Jets originating from either an u -, d - or s -quarks or gluons.

- **JetFitter** exploits the topological structure of the decay chain of heavy flavour hadrons inside a jet. Jets originating from heavy flavour hadrons typically exhibit both a larger number of vertices and a larger number of tracks from vertices (with at least two tracks).

The output weights obtained from these algorithms are combined by multi-variate algorithms (MVA) [130]. The b -tagging algorithm used during Run-II is known as MV2c10 [108]. The MV2c10 algorithm collects the output variables of these algorithms and implements a Boosted Decision Tree (BDT) to combine them in order to discriminate between b -tagged and non b -tagged jets. The algorithm is trained on jets from $t\bar{t}$ events, where b -jets are considered as signal and c -jets and light-jets are considered as background. The rejection efficiency of light-jets versus c -jets is changed by altering the fraction of c -jets in the training. The MV2c10 variation is trained using a composition of 7% c -jets and mixture of 93% light-jets [131]. The Operating-Point (OP) of the algorithm is the particular selection placed on the output score of the algorithm that corresponds to a given b -tagging efficiency. The value chosen corresponds to 77% b -jet efficiency. This 77% refers to the b -tagging acceptance efficiency, representing that from all true b -jets, 77% will be correctly identified by the algorithm. Figure 3.4 presents the MV2c10 BDT output for the signal and background components used to characterise the b -tagging performance in MC simulated events. A p_T -dependent scale factor is then applied to the resultant b -jet that corrects for the differences in b -tagging efficiency between data and MC using a $t\bar{t}$ enriched sample [132, 133].

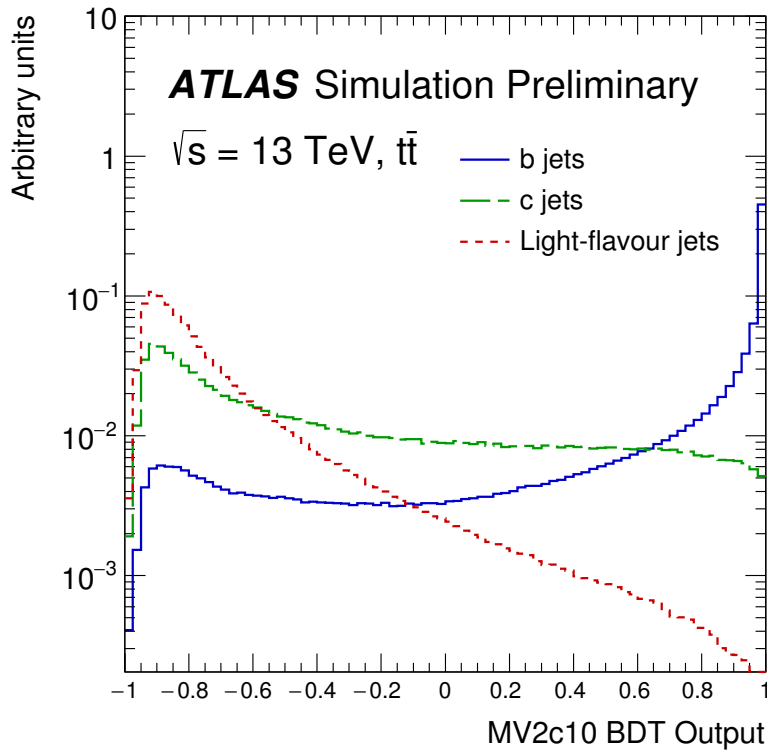


FIGURE 3.4: MV2c10 BDT output for b -jets (solid blue), c -jets (dashed green) and light-jets (dotted red). Taken from [108].

3.6 Missing Transverse Momentum

During proton collisions, particles that do not interact with the ATLAS detector can be produced and hence are able to traverse the entire detector without detection. When considering the SM, the neutrino is the only particle that is not expected to interact with the detector. However, when considering R-parity conserving supersymmetry, the LSP ($\tilde{\chi}_1^0$) is also predicted to exhibit this behaviour and hence the ability to determine the momentum, energy and direction of these particles becomes vital for searches for supersymmetry.

The presence of these particles can only be inferred by imposing momentum conservation. However, during proton collisions, the fraction of energy which the partons carry is unknown and so the initial energy of the collision is also unknown. If, however, the momentum conservation is considered only in the transverse plane to the beam, then the sum of the initial transverse momentum is zero. Therefore, if the sum of the momenta in the transverse plane of all particles produced during the collision is non-zero, then we can infer the magnitude and direction of the ‘missing’ transverse momentum, $\mathbf{p}_T^{\text{miss}}$, such that the conservation of momentum holds i.e. so the sum of the transverse momentum in the final state is also equal to zero. The modulus of the missing transverse momentum is referred to as the missing transverse energy, E_T^{miss} , and is defined as the negative vectorial sum of the transverse energy of all energy deposits and tracks within the detector [134, 135]. Figure 3.5 depicts an event containing missing transverse momentum along with other detectable particles. The energy that the LSP is expected to carry could be significantly larger than the missing energy expected from SM processes, providing an exploitable kinematic feature when attempting to observe supersymmetry.

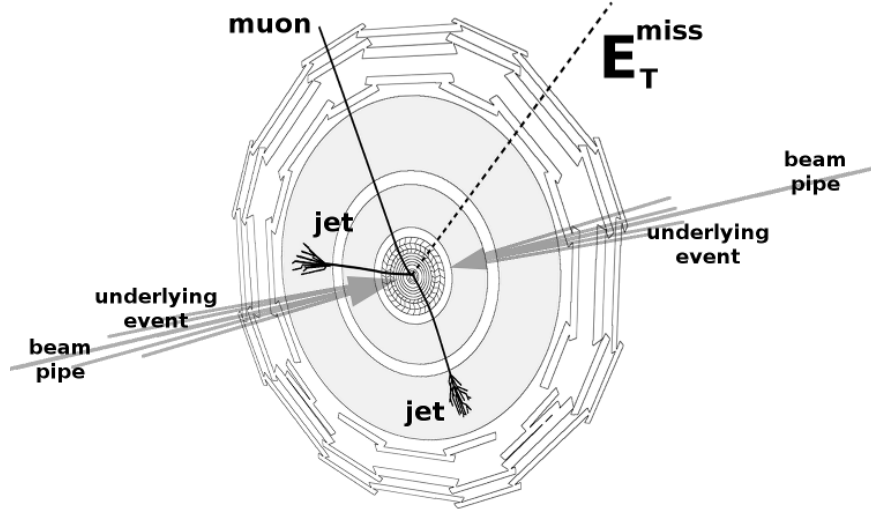


FIGURE 3.5: Depiction of an event containing missing transverse momentum along with other detectable particles. Taken from [138].

The E_T^{miss} reconstruction process begins with reconstructed, calibrated particles that are used to determine the imbalance of the transverse momentum within an event. This procedure uses information from reconstructed particles in the event opposed to performing a simple sum of the energy deposits, as it provides an overall improved E_T^{miss} resolution since each of the reconstructed particles can be specifically calibrated depending on their identification. Tracks and energy deposits are reconstructed in a defined order to avoid overlap between particles. If an energy deposit has already been associated to a particle, then this energy deposit will not be considered for subsequent particle reconstructions.

The terms for the charged leptons, photons and jets are calculated from the calibrated energy deposits within $|\eta| < 4.9$. The muon term is calculated from the momentum of muons tracks that are reconstructed within $|\eta| < 4.9$. The order is as follows: electrons, photons, jets and muons.

The missing transverse momentum vector $\mathbf{p}_T^{\text{miss}}$ is defined as:

$$\mathbf{p}_T^{\text{miss}} = \mathbf{p}_T^{\text{miss, e}} + \mathbf{p}_T^{\text{miss, } \gamma} + \mathbf{p}_T^{\text{miss, jets}} + \mathbf{p}_T^{\text{miss, } \mu} + \mathbf{p}_T^{\text{miss, soft}} \quad (3.4)$$

From this, E_T^{miss} is defined as the magnitude of this quantity with an azimuthal angle ϕ^{miss} . The soft term is calculated using only the tracks from the ID that are not associated to any reconstructed particles, but are associated to the primary vertex. This term is abbreviated as the TST, the Track Soft Term. Quality selections are applied to the tracks used in the calculation [134, 135].

The E_T^{miss} originating from undetectable particles is often referred to as *true* missing transverse energy. However, *fake* contributions to the E_T^{miss} can arise from detector inefficiencies, such as mis-reconstructed particles, dead or noisy active regions of the detector or the intrinsic detector resolution, amongst others. It is of particular importance to accurately determine the fake contribution to the E_T^{miss} originating from pile-up. With the inclusion of more particles in a given event, the E_T^{miss} calculation can be severely affected.

Chapter 4

Searching Beyond the Standard Model using the Higgs Boson

The supersymmetric partners of the third generation quarks: the top- and bottom-squarks, might be significantly lighter than the other supersymmetric quarks, as was motivated in Section 1.6. Their masses are predicted to be around the electroweak scale and hence their production could be abundant at the LHC. Therefore, the search for bottom-squark production poses a well-motivated approach when attempting to discover supersymmetry at the LHC. Documented is the BSM search for direct bottom-squark pair production in final states containing multiple b -tagged jets and large missing transverse momentum performed using the full ATLAS Run 2 dataset, corresponding to 139 fb^{-1} , at a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$. At the time of publication, the results of this search provided world-leading exclusion limits at the 95% confidence level (CL) on $\tilde{b}_1 \rightarrow b\tilde{\chi}_2^0$ decays and is to be published in the Journal of High Energy Physics [139].

4.1 Introduction and Motivation

The majority of previous ATLAS searches for the bottom-squark focus on the direct pair production of $\tilde{b}_1$, considering channels with $\mathcal{B}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0)=100\%$ and $\mathcal{B}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^\pm)=50\%$, $\mathcal{B}(\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm)=50\%$, where $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 5 \text{ GeV}$ and hence the decay $\tilde{\chi}_1^\pm \rightarrow W^*\tilde{\chi}_1^0$ occurs via an off-shell W , producing soft decay products not measurable by ATLAS. No significant excess over the SM expectation was observed in these analyses [64–69, 140].

However, the bottom-squark can decay via different processes and is dependent on the sparticle mass spectrum and on other model parameters, as discussed in Section 1.7. Scenarios in which $|M_1| \leq |\mu|$ and $|M_2| > |M_1|$ result in a composition of the $\tilde{\chi}_1^0$ that is mostly bino. This leads to a stronger coupling of $h\tilde{\chi}_2^0\tilde{\chi}_1^0$ than $Z\tilde{\chi}_2^0\tilde{\chi}_1^0$ and hence $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ decays become the dominant mode. When the LSP is bino-like and the $\tilde{\chi}_2^0$ is a wino–higgsino mixture, the branching ratio ($\mathcal{B}$) of $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ is enhanced relative to the other possible $\tilde{\chi}_2^0$ decays, as is previously depicted in Figures 1.5 and 1.6.

A motivated simplified model is used for the interpretation of the results of a search for new physics through complex decay chains of the bottom-squark in final states containing multiple jets originating from the fragmentation of b -quarks (b -jets) and large missing transverse momentum. Figure 4.1 presents the schematic diagram of the targeted scenario. A unique signature of pair produced bottom-squarks is targeted, where the simplified model used assumes they are the only

supersymmetric particle produced at the LHC and that they decay with a 100% branching ratio to a b -quark and $\tilde{\chi}_2^0$. The $\tilde{\chi}_2^0$ then subsequently decays with a 100% branching ratio to a Higgs boson and a $\tilde{\chi}_1^0$, the latter of which is stable and the LSP. The Higgs boson in the simplified model is the SM Higgs boson. Since the dominant decay of the Higgs is to a b -quark pair with $\mathcal{B} = 58\%$ [141, 142], a unique signature of large missing transverse momentum and up to six b -jets may be present. In this way, the Higgs boson can be used as a probe to search for BSM physics.

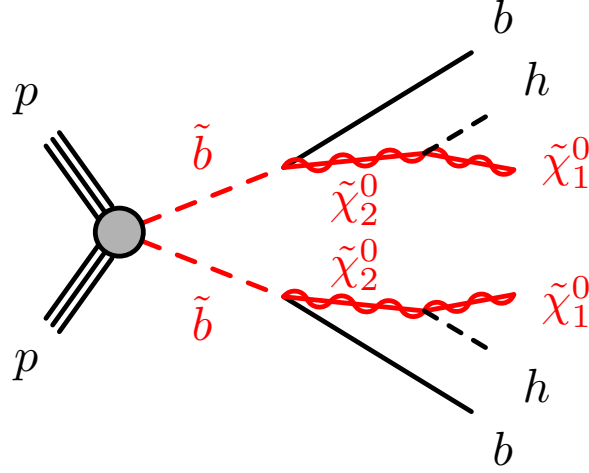


FIGURE 4.1: Graphical representation of the signal phenomenology targeted by the analysis presented in this thesis. Bottom-squarks are produced in pairs and subsequently decay to $b\tilde{\chi}_2^0$ with 100% branching ratio. The two $\tilde{\chi}_2^0$ particles decay to $h\tilde{\chi}_1^0$ also with 100% branching ratio.

There are several SM background processes that must be considered when analysing such a final state: $t\bar{t}$ pair production; Z boson production in association with heavy-flavour (HF) jets, referred to as Z +jets; single-top production; $t\bar{t}$ production in association with a vector boson ($t\bar{t} + W/Z$); $t\bar{t}$ production with an associated Higgs boson ($t\bar{t} + h$); W boson production in association with HF-jets, referred to as W +jets and diboson production.

The main SM processes contributing to the background arise from top production, significantly dominated by top-quark pairs produced in association with two b -quarks arising from gluon splitting $g \rightarrow b\bar{b}$. If the leptons produced during semi-leptonic $t\bar{t}$ decay are either lost (out of acceptance) or not correctly reconstructed, then a final state of zero-leptons, four b -jets and E_T^{miss} could be measured. A similar decay scenario is expected for the case of single-top production. Fully hadronic $t\bar{t}$ and single-top events do not contain sufficient E_T^{miss} to contribute significantly to the background. The Z +jets background is also expected to contribute significantly, if the Z boson is produced in association with two b -jets, then the Z can decay via $Z \rightarrow \nu\nu$, resulting in a b -jets and E_T^{miss} final state.

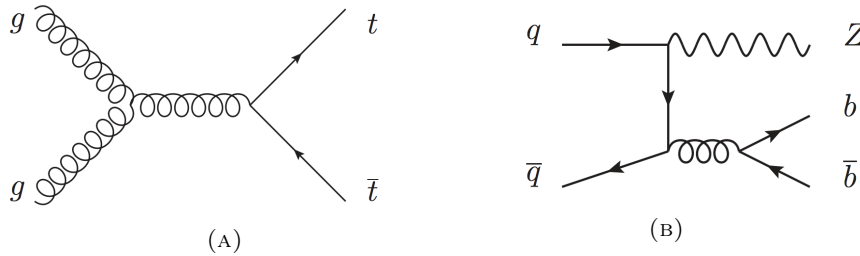


FIGURE 4.2: Example Feynman diagrams of two of the dominant SM processes in the analysis. (A) $t\bar{t}$ pair production, taken from [198]. (B) Z +jets production, taken from [199].

The W +jets background may contribute to this final state in a similar way as with the semi-leptonic $t\bar{t}$ background, where a lepton is lost or mis-reconstructed ($W(l\nu)$ +jets). The b -jets can arise from this process through gluon splitting. The $t\bar{t} + W/Z$ background can produce a similar final state through particular decays of either the W boson ($W(l\nu)$ +jets) or the Z boson ($Z(\nu\nu)$ +jets). The diboson (ZZ , WZ , WW) and $t\bar{t} + h$ production are expected to negligibly contribute in this analysis given their rarity in production within the SM and are expected to contribute only a small number of events to the targeted final state.

The multijet background refers to all-hadronic backgrounds including those originating from hadronic W +jets, Z +jets and $t\bar{t}$ backgrounds and must be considered when searching for a zero-lepton final state topology. This background arises from the mis-reconstruction of jets, resulting in ‘fake’ E_T^{miss} in an event. The probability for ATLAS to mis-measure these backgrounds, whereby large values of E_T^{miss} can arise, increases with the hadronic activity of the event. Selections on particular variables have shown to significantly reduce the contribution of this background to a negligible amount and is detailed in Section 4.3.

Bottom-squark searches performed prior to the presented analysis typically introduce fewer new particles within simpler decay chains. The advantage of considering a complicated process is that it produces a unique final state that is less likely to have been produced through known SM physics than the final states targeted by previous searches, presenting an opportunity to more effectively identify and reject events originating from SM processes.

The targeted signature contains three free parameters, namely the masses of the bottom-squark, the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$. To reduce its dimensionality, two independent assumptions are implemented that intend to fix one of the three free parameters. Thus, in both cases a two-dimensional model is considered.

The first simplified model assumes that the mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is fixed at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}$ and are henceforth referred to as the DM130 signal models. This assumption is placed to kinematically verify the production of an on-shell Higgs boson. The model parameter space is expressed as a function of the masses of the bottom-squark and $\tilde{\chi}_1^0$. Models are considered in which the bottom-squark masses range from 400 GeV up to 1400 GeV and $\tilde{\chi}_1^0$ mass values are considered from 1 up to 800 GeV. The individual mass scenarios available for optimisation and interpretation of the results are depicted as points in Figure 4.3(a).

The second simplified model considered fixes the mass of the $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ and are henceforth referred to as the M60 signal models. As is previously discussed in Section 1.6, in R-parity conserving scenarios the LSP is a candidate for dark matter. However bino-like LSP models tend to produce an overabundance of LSPs during the early universe [143] compared to the dark matter relic density that is observed today [144], unless there exists an efficient annihilation mechanism that could explain this difference in values. An appealing scenario is the Higgs-pole annihilation where the LSP has a mass $m(\tilde{\chi}_1^0) \simeq m(h)/2$ and hence the choice of $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ is justified [145]. Bottom-squarks with masses from 150 GeV up to 1600 GeV are considered and $\tilde{\chi}_2^0$ masses are considered from 200 up to 1595 GeV. The individual mass scenarios available for optimisation and interpretation of the results are depicted as points in Figure 4.3(b).

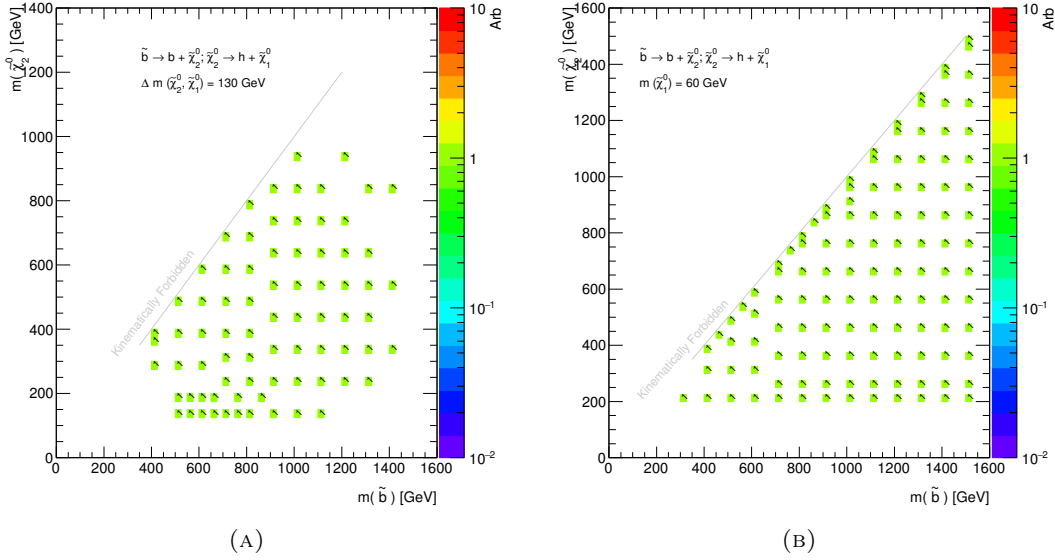


FIGURE 4.3: Generated signal mass scenarios on the parameter space of the simplified models considered. (A) shows the signal phase-space considering $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, the minimum $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$ chosen is 10 GeV. (B) shows the signal phase-space under the $m(\tilde{\chi}_1^0) = 60$ GeV assumption, the minimum $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$ considered is 5 GeV.

4.2 Datasets and Simulated Samples

The dataset analysed in this search corresponds to the data collected by the ATLAS experiment during the 2015, 2016, 2017 and 2018 proton-proton LHC collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV, with a peak instantaneous luminosity $\mathcal{L} = 1.4 \cdot 10^{34} \text{ cm}^2 \text{ s}^{-1}$. The 2015 and 2016 datasets correspond to an integrated luminosity of 3.2 fb^{-1} and 32.9 fb^{-1} respectively, summing to a total of $L_{2015-2016} = 36.1 \pm 2.1 \text{ fb}^{-1}$ with an average number of interactions per proton-proton beam bunch crossing $\langle \mu \rangle = 20$. A total integrated luminosity $L_{2017} = 44.3 \pm 2.4 \text{ fb}^{-1}$ was recorded during the 2017 data taking campaign with $\langle \mu \rangle = 37.8$. Finally, a total integrated luminosity $L_{2018} = 58.45 \pm 1.2 \text{ fb}^{-1}$, was recorded during the 2018 data collection campaign with $\langle \mu \rangle = 37.0$. Data events are only considered during stable beam conditions and with all relevant detector systems operational. After data quality requirements, the data sample amounts to an integrated luminosity of $139.0 \pm 2.4 \text{ fb}^{-1}$. The uncertainty on this measurement is derived from a van der Meer (vdM) scan, and is detailed in Ref. [146].

The final state is expected to contain zero-leptons and large E_T^{miss} , therefore E_T^{miss} triggers are used to collect the data. Events are required to pass a E_T^{miss} trigger [147] which is fully efficient for events with reconstructed $E_T^{\text{miss}} > 250$ GeV. Additional single-lepton triggers requiring electrons or muons are used to estimate the SM backgrounds, with an offline selection of $p_T(\ell) > 27$ GeV used to ensure the trigger is fully efficient ($\ell = e, \mu$).

Monte Carlo (MC) simulated samples [148] are a vital component of modern particle physics analysis. They are used to develop selections that can effectively discriminate between signal and background events by studying kinematic properties. They are also used to study detector acceptance and performance through reconstruction efficiencies of a given process. Most crucially to the analysis presented, they are used to model the background processes and allow for a calculation of the expected event yields for each SM process, while also modelling the theoretical supersymmetric signal, and hence their ability to accurately model these processes is of crucial importance when searching for new phenomena.

Given the large number of particles produced during proton-proton collisions, with energies typically ranging over several orders of magnitude, the simulation of such events is a non trivial task. This is furthered by the complexity of the protons substructure and the properties of QCD. The modelling process is required to consider the interactions between quarks and gluons within the colliding protons, initial and final state radiation of particles and the modelling of additional interactions that occur during the collision. The modelling of a proton-proton collision event can be described through three main processes and is depicted in Figure 4.4.

Hard Scatter

This is the primary interaction between constituent partons of the colliding protons. The Matrix Element (ME) is calculated using perturbation theory to a limited order, and is based on the relevant Feynman diagram. This is depicted in Figure 4.4 as the hard scatter process between two gluons from the colliding protons that produce a top-quark pair in association with a Higgs boson, represented by the three red circles.

Parton Shower

Following is the shower evolution, known as the parton shower (PS), whereby the incoming and outgoing partons begin to radiate other partons or split several times in a process referred to as a shower. This step is depicted by the red lines.

Hadronisation

The final stage is the hadronisation process, shown in green. This stage occurs once the particles have lost energy and are at low momentum, in the scale at which confinement occurs. The strongly-interacting particles group together to form colourless hadrons that are then measured in the detector. In this regime perturbative QCD breaks down and hence MC modelling of the hadronisation process is performed using empirical methods since it cannot be analytically predicted.

In addition to these processes, charged particles can also emit EM radiation throughout this entire process, shown in yellow, and additional interactions can occur between other partons of the interacting protons, shown in purple, and is referred to as a Multiple Parton Interaction (MPI), or the underlying event. In addition to MPI interactions, collisions between other protons in the colliding bunch can also occur, and are referred to as pile-up interactions.

The number of expected events for a given process using a MC generator is calculated using Equation 4.1:

$$N_{\text{Exp.Events}} = \frac{\mathcal{L}_{\text{data}} \cdot \alpha \cdot \sigma_{\text{process}} \cdot \epsilon \cdot k}{\mathcal{L}_{\text{generated}}} \cdot N_{\text{Raw Events}} \quad (4.1)$$

For a given analysis region, the expected number of events can be calculated and is dependent on: the total luminosity collected by the detector, $\mathcal{L}_{\text{data}}$; a scale factor that is applied to reconstructed particles in order to correctly reproduce the detector response in data, α ; the production cross-section of a given process, σ_{process} ; the efficiency of filters used during sample generation, ϵ ; the k -factor that is used to scale the cross-section to include an additional order in perturbation theory, k ; and the unscaled number of MC events that pass the selection, $N_{\text{Raw Events}}$.

In the following, the generators relevant to the presented analysis are briefly described:

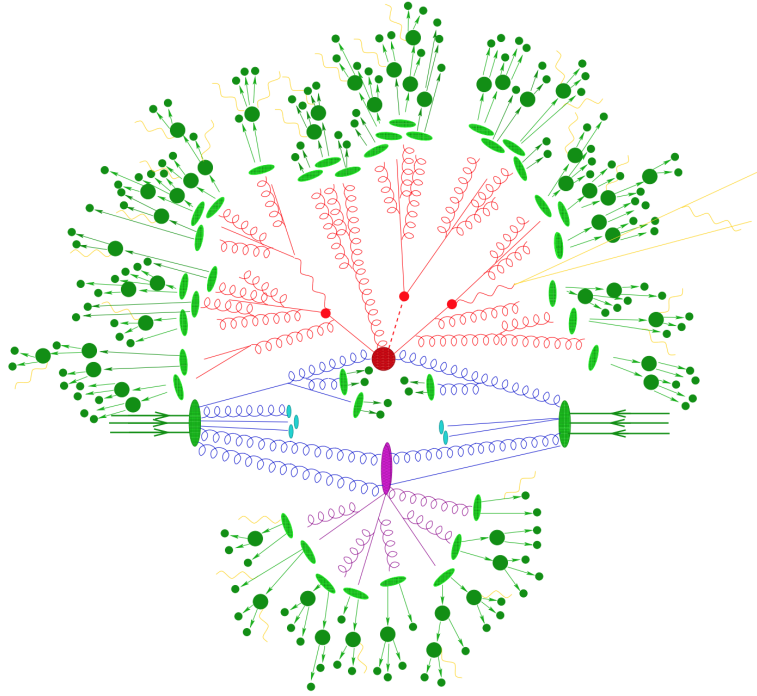


FIGURE 4.4: Depiction of proton-proton collision modelling $t\bar{t} + h$ production. The constituent partons of the initial protons are represented in blue. The hard scatter process is represented by the large red circle and produces a top-quark pair associated with a Higgs boson. The subsequent decays and QCD radiation of the PS process is represented in red. The hadronisation process is depicted in green. Additionally, secondary interactions are shown in purple and photon emission is shown in yellow. Taken from [151].

MADGRAPH

MADGRAPH [149] is a leading-order ME generator that was extended to allow for the inclusion of loop diagrams [150]. MADGRAPH generates the Feynman diagrams and calculates the ME of a pre-defined process. For simulation of the PS and hadronisation, MADGRAPH is interfaced with a PS generator (typically PYTHIA).

SHERPA

SHERPA [151] is a general-purpose generator, capable of ME calculation and PS description. The ME calculation is at next-to-leading order (NLO) for up to two partons, with four additional partons able to be generated at leading order (LO) using the COMIX [152] and OPENLOOPS [153] ME generators. This is then interfaced with an internal PS algorithm [154], which follows the ME+PS@NLO prescription [155].

PYTHIA

PYTHIA [156] is a general-purpose generator. It is capable of leading-order ME calculation, however it is more commonly used exclusively for the PS and hadronisation description and is interfaced with a higher order ME generator, such as MADGRAPH.

POWHEG

Although POWHEG [157] is not capable of simulating the entire chain, it is, however, capable of calculating the hard scatter process with NLO accuracy, which can then be interfaced with any modern PS generator.

The configuration of these generators typically include parameters that can be varied in order to evaluate the corresponding uncertainties: the matrix element matching scale (CKKW) is the merging scale used during calculation of the overlap of jets from ME and from PS; the renormalisation scale is the scale at which the strong coupling constant (α_s) is calculated for the initial hard scattering process; the factorisation scale is used in the PDF and cross-section calculations; and the resummation scale is used in the algorithm modelling the PS to begin the soft emission process.

The MC events of both SM processes and the signals of interest were generated, reconstructed and scaled with a pile-up profile to match the corresponding $\langle\mu\rangle$ for each of the data periods. A reweighting procedure is implemented to the MC campaigns of the differing data periods in order to match the corresponding μ profile measured in data and is based on energy-scale calibrations, scale factors and uncertainties. Simulated events are passed through a detector simulation in order to replicate the interaction of particles with the ATLAS detector material and support structure in order to produce data-like events. All MC samples were produced using the ATLAS simulation infrastructure [158] and GEANT 4 [159], or a faster simulation based on a parameterisation of the calorimeter response and GEANT 4 for the other detector systems. Information on the event generator, PS and hadronisation generator, cross-section normalisation, parton distribution function (PDF) set and underlying-event tuned parameter set (tune) of the samples used during the presented analysis are given in Table 4.1.

The supersymmetry signal samples were generated with MADGRAPH v2.6.2 [149] at LO and interfaced to PYTHIA v8.230 [156] for the modelling of the PS, hadronisation and the underlying-event with the A14 [160] set of tuned parameters. The ME calculation was performed at tree level and includes the emission of up to two additional partons. The ME–PS matching was done using the CKKW-L [161] prescription, with a matching scale set to one quarter of the bottom-squark mass. The NNPDF23L0 [162] PDF set was used. Signal cross-sections were calculated to approximate next-to-next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-next-to-leading-logarithm (approximate NNLO+NNLL) [163–166] accuracy. The nominal cross-section and its uncertainty were derived using the PDF4LHC15_mc PDF set, following the recommendations of Ref. [167]. For $\tilde{b}_1$ masses between 400 GeV and 1.5 TeV, the cross-sections range from 0.21 pb to 0.26 fb, with uncertainties from 6% to 17%.

For the background estimation, the samples were simulated using different MC generator programs depending on the process. Pair production of top-quarks, $t\bar{t}$, was generated using POWHEG-BOX v2 [157] interfaced with PYTHIA v8.230 and the A14 tune with the NNPDF23L0 PDF set for the ME calculations. The h_{damp} parameter in POWHEG-BOX, which controls the p_T of the first additional emission beyond the Born level and thus regulates the p_T of the recoil emission against the $t\bar{t}$ system, was set to 1.5 times the top-quark mass ($m_t = 172.5\text{GeV}$) as a result of studies documented in Ref. [168].

The generation of single top-quarks in the Wt -channel, s -channel and t -channel production modes was performed by POWHEG-BOX v2 similarly to the $t\bar{t}$ samples. For all processes involving top-quarks, top-quark spin correlations were preserved. All events with at least one leptonically decaying W boson were retained. Fully hadronic $t\bar{t}$ and single-top events do not contain sufficient E_T^{miss} to contribute significantly to the background.

The production of $t\bar{t}$ pairs in association with electroweak vector bosons (W , Z) or Higgs bosons was modelled by samples generated at NLO using MADGRAPH v2.2.3 and showered with PYTHIA v8.212.

Events containing W or Z bosons with associated jets, including jets from the fragmentation of heavy-flavour quarks, were simulated using the SHERPA v2.2.1 [151] generator. Matrix elements were calculated for up to two additional partons at NLO and four partons at LO using the COMIX [152] and OPENLOOPS [153] ME generators and were merged with the SHERPA PS using the ME+PS@NLO prescription [154, 155]. The NNPDF30NNLO [162] PDF set was used in conjunction with a dedicated PS tune developed by the SHERPA authors.

Diboson processes were also simulated using the SHERPA generator using the NNPDF30NNLO PDF set in conjunction with a dedicated PS tune. They were calculated for up to one (ZZ) or zero (WW , WZ) additional partons at NLO and up to three additional partons at LO.

Other potential sources of backgrounds, such as the production of three or four top-quarks or three gauge bosons, are found to be negligible. Finally, contributions from multijet backgrounds are estimated from data using a jet smearing procedure described in Ref. [169] and are found to be negligible in all regions and is described in Section 4.4. The multijet background is no longer considered in the analysis.

All background processes are normalised to the best available theoretical calculation for their respective cross-sections. The NLO $t\bar{t}$ inclusive production cross-section is corrected to the theory prediction at NNLO in QCD including the resummation of NNLL soft-gluon terms calculated using Top++2.0 [170–176]. Samples of single-top events are normalised to the NLO cross-sections reported in Refs. [177–179].

For all samples, except those generated using SHERPA, the EVTGEN v1.2.0 [180] program was used to simulate the properties of the bottom- and charm-hadron decays. All simulated events include a modelling of contributions from pile-up by overlaying minimum-bias pp interactions from the same (in-time pile-up) and nearby (out-of-time pile-up) bunch crossings simulated in PYTHIA v8.186 and EVTGEN v1.2.0 with the A3 [181] tune and MSTW2008LO PDF set [182].

Physics Process	Event Generator	Parton Shower Generator	Cross-Section Normalisation	PDF Set	Tune
SUSY Signals	MADGRAPH v2.6.2 [150]	PYTHIA 8.230 [156]	NNLO+NNLL [163–166]	NNPDF23LO [162]	A14 [160]
$t\bar{t}$	POWHEG-BOX v2 [157]	PYTHIA 8.230	NNLO+NNLL [171–176]	NNPDF23LO	A14
Z +jets	SHERPA 2.2.1 [151]	SHERPA 2.2.1	NNLO [183]	NNPDF30NNLO [162]	SHERPA default
single-top	POWHEG-BOX v2	PYTHIA 8.230	NNLO+NNLL [178]	NLOCT10 [184]	Perugia2012 [185]
$t\bar{t}W/Z$	MADGRAPH v2.2.3	PYTHIA v8.212 [186]	NLO [150]	NP23LO	A14
$t\bar{t} + h$	MADGRAPH v2.2.3	PYTHIA v8.212	NLO [187]	NNPDF23	A14
W +jets	SHERPA v2.2.1	SHERPA v2.2.1	NNLO [183]	NNPDF30NNLO	SHERPA default
Diboson	SHERPA v2.2.1	SHERPA v2.2.1	NLO	NNPDF30NNLO	SHERPA default

TABLE 4.1: Simulated signal and background event samples presenting the corresponding event generator, parton shower generator, cross-section normalisation, PDF set and underlying-event tune used for each process.

4.3 Event Reconstruction and Selection

This search is based upon a selection of events with many b -jets, large missing transverse momentum and no charged leptons (electrons and muons) in the final state. All events are required to have a reconstructed primary vertex that is consistent with the beamspot envelope and is reconstructed with at least two associated tracks in the ID with $p_T > 500$ MeV. If more than one vertex passing the above requirements is found, the vertex with the largest sum of the squares of transverse momenta of associated tracks is chosen [106].

Jet candidates are reconstructed from three-dimensional clusters of energy in the calorimeter with the anti- k_t jet algorithm using a radius parameter of $R = 0.4$. A jet energy scale (JES) correction is applied and is derived from data and simulation [127] in order to calibrate the reconstructed jets. A set of quality criteria are applied to identify jets that arise from non-collision sources or detector noise [128] and any event that contains a jet not meeting these requirements is removed. Additional jets that arise from pile-up interactions are rejected by applying additional track-based selections to jets with $p_T < 120$ GeV and $|\eta| < 2.4$ [188], and the jet momentum is corrected by subtracting the expected average energy contribution from pile-up using the jet area method [119]. Jets are classified as either ‘baseline’ or ‘signal’; baseline jets are required to have $p_T > 20$ GeV and $|\eta| < 4.8$, whilst signal jets are selected after resolving overlaps with electrons and muons, as is described below, and must pass tighter requirements of $p_T > 30$ GeV and $|\eta| < 2.8$. This additional p_T requirement reduces the sensitivity of the analysis to pile-up jets that survive the JVT selection in the range $p_T \in [20, 30]$ GeV.

Signal jets are identified as b -jets if they are within $|\eta| < 2.5$ and $p_T > 30$ GeV and are tagged by a multivariate algorithm that takes as input information about the impact parameters of ID tracks, the presence of displaced secondary vertices and the reconstructed flight paths of b - and c -hadrons inside the jet. The b -tagging algorithm used has an efficiency of 77%, determined in a sample of simulated $t\bar{t}$ events. This was chosen during the optimisation procedure and the corresponding misidentification rate is 20% for c -jets and 0.9% for light-flavour jets. To compensate for differences in the b -tagging efficiencies and mis-tag rates between data and MC simulation, correction factors are derived from data and applied to the samples of simulated events. Details can be found in Ref. [131].

	Selection
Baseline Jets	$p_T > 20$ GeV $ \eta < 4.8$
Signal Jets	$p_T > 30$ GeV $ \eta < 2.8$
Signal b-jets	$p_T > 30$ GeV $ \eta < 2.5$

TABLE 4.2: Summary of the jet selections.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter, they are then matched to a track in the ID and are required to satisfy a set of ‘loose’ quality criteria [112]. They are also required to reside within $|\eta| < 2.47$ and have $p_T > 4.5$ GeV. Muon candidates are reconstructed by matching tracks in the ID with tracks in the muon spectrometer.

Muon candidates that have a transverse (longitudinal) impact parameter relative to the primary vertex larger than 0.2 mm (1 mm) are rejected in order to reduce sensitivity to muons arising from cosmic rays. Muon candidates are also required to satisfy a set of ‘medium’ quality criteria [117] and have $|\eta| < 2.5$ and $p_T > 4$ GeV. Electron (muon) candidates are matched to the primary vertex by requiring the transverse impact parameter to satisfy $|d_0|/\sigma(d_0) < 5$ (3), and the longitudinal impact parameter to satisfy $|z_0 \sin \theta| < 0.5$ mm. Lepton candidates remaining after resolving overlaps with baseline jets are called ‘baseline’ leptons. In the control regions defined in Section 4.7, where tighter lepton identification is required, ‘signal’ leptons are chosen from the baseline set with $p_T > 20$ GeV and are required to be isolated from other activity in the detector by imposing criteria designed to accept at least 95% of leptons from Z boson decays; details can be found in Ref. [111]. In the dilepton control region where the single-lepton triggers are used, the leading lepton is required to have $p_T > 27$ GeV, which ensures full efficiency of the single-lepton triggers. Signal electrons are further required to satisfy ‘tight’ quality criteria [112]. The MC events are corrected to account for differences in the lepton trigger, reconstruction and identification efficiencies between data and MC simulation.

	Selection
Baseline Electrons	$p_T > 4.5$ GeV $ \eta < 2.47$ ‘loose’ isolation [112]
Signal Electrons	$p_T > 20$ GeV $ \eta < 2.47$ ‘tight’ isolation [112]

TABLE 4.3: Summary of the electron selections.

	Selection
Baseline Muons	$p_T > 4$ GeV $ \eta < 2.5$ ‘medium’ isolation [117]
Signal Muons	$p_T > 20$ GeV $ \eta < 2.47$ ‘tight’ isolation [117]

TABLE 4.4: Summary of the muon selections.

In a process referred to as overlap-removal, possible reconstruction ambiguities between baseline electrons, muons and jets are resolved by firstly removing electron candidates that share an ID track with a muon candidate. Jet candidates are then removed if they are within $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ of an electron candidate. Electron candidates are then removed if they are within $\Delta R = 0.4$ of a jet. Muons are discarded if they reside within $\Delta R = 0.4$ of any remaining jets, except in cases where the number of tracks associated to the jet is less than three, whereby the muon is kept and the jet is discarded.

Hadronically decaying τ leptons are not considered in the analysis, however the following τ -veto procedure is applied in order to discard events that contain τ -like particles. Candidates (τ_{cand}) are identified as jets that have $|\eta| < 2.5$ and less than five ID tracks of $p_T > 500$ MeV. If an event contains a tau candidate that is closely separated in azimuthal angle to the $\mathbf{p}_T^{\text{miss}}$ ($\Delta\phi(E_T^{\text{miss}}, \tau_{\text{cand}}) < \pi/3$), then the event is rejected.

The missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ is defined as the negative vector sum of the p_T of all selected and calibrated particles (electrons, muons, photons [115] and jets) in the event, while an additional term is included to account for soft energy in the event that is not associated with any of the selected particles [134]. This soft term is calculated from ID tracks with p_T above 500 MeV that are matched to the primary vertex, thus ensuring a reduction in sensitivity to pile-up events [125, 135].

4.4 Analysis Strategy

In the simplified model targeted by this analysis, several reconstructable final states with varying kinematic properties are possible and depend on the decay mode of the Higgs bosons and on the masses of the $\tilde{b}_1$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. Three sets of non-orthogonal signal regions (SRs) are defined to target different mass hierarchies of the supersymmetric particles involved. These definitions exploit various discriminating observables and implement algorithms developed to explicitly reconstruct Higgs boson candidates in the decay chain. In this way, the recently discovered Higgs boson can be used as a probe to explore BSM physics. Given the fully hadronic final state, events with charged leptons are vetoed in all SRs. Events with one or two charged leptons are used to define control regions (CRs), used for the estimation of the main SM backgrounds. Additionally, events with zero charged leptons are used to define validation regions (VRs) to ensure that the background estimation method is effective and are introduced in Section 4.7. An optimisation procedure aims to maximise the yield of bottom-squark pair production events while reducing SM background contributions by identifying the optimal event selection cuts. It is performed for the two simplified model scenarios introduced in Section 4.1.

The event selection criteria are defined by implementing kinematic requirements on the reconstructed particles and the event variables described below. For these definitions, signal jets are used and are ordered by decreasing transverse momentum.

- N_{jets} : the number of signal jets.
- $n_{b\text{-jets}}$: the number of b -jets.
- $\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})]$: the minimum azimuthal distance between the four highest- p_T jets and the $\mathbf{p}_T^{\text{miss}}$. This variable is particularly effective in rejecting multijet background events containing a large amount of E_T^{miss} due to mismeasured jets. Typically, multijet background events exhibit low values of this variable and studies using data-driven multijet estimates indicate that a selection of $\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})] > 0.4$ is sufficient to reduce the multijet background to a negligible level.
- $\Delta\phi(j_1, E_T^{\text{miss}})$: the azimuthal distance between the highest- p_T jet and the E_T^{miss} . This variable is used to select events where the $\mathbf{p}_T^{\text{miss}}$ is expected to be recoiling against the leading jet.
- m_{eff} : the effective mass [189] of an event is defined as the scalar sum of the p_T of all signal jets and the E_T^{miss} , i.e.:

$$m_{\text{eff}} = \sum_{i \leq N_{\text{jets}}} (p_T^{\text{jet}})_i + E_T^{\text{miss}}.$$

- $\mathcal{S}$: referred to as the ‘object-based E_T^{miss} -significance’ [190] is defined as follows:

$$\mathcal{S} = \sqrt{\frac{|\mathbf{p}_T^{\text{miss}}|^2}{\sigma_L^2(1 - \rho_{LT}^2)}}.$$

The total momentum resolution of all jets and leptons, for a given p_T and $|\eta|$, is determined from parameterised MC simulation that effectively reproduces the resolution that is measured in data. σ_L is the total momentum resolution after a rotation into the longitudinal (parallel to the $\mathbf{p}_T^{\text{miss}}$) plane. The quantity ρ_{LT} is a correlation factor between the longitudinal and transverse momentum resolution of each lepton or jet. The significance $\mathcal{S}$ is used to discriminate between events where the E_T^{miss} arises from invisible particles in the final state, and from events where the E_T^{miss} arises from mismeasured particles and jets. This variable is also useful in discriminating between signal events with large E_T^{miss} and Z +jets events with medium-to-low E_T^{miss} .

Selections are also applied to the p_T of the leading jet and the leading b -jet. In all SRs, events that contain baseline leptons with $p_T > 10$ GeV are rejected, as well as those that contain τ -lepton candidates that are azimuthally separated with the $\mathbf{p}_T^{\text{miss}}$ within $\Delta\phi = \pi/3$. Only events with $E_T^{\text{miss}} > 250$ GeV are accepted in order to ensure full efficiency of the E_T^{miss} trigger.

The event kinematics targeted by each of the three SRs are depicted in Figure 4.5. The first SR, SRA, is designed to target the ‘bulk’ region of both signal models covering the vast majority of mass eventualities, with moderate- to high-mass splitting between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$. In these scenarios all of the b -jets from both the bottom-squarks and Higgs boson decays are at a relatively high p_T and can be reconstructed in the detector. The b -jets from the Higgs boson can be isolated by firstly identifying and removing the ones most likely to have originated from the initial bottom-squark decays and then by comparing the angular separation between the remaining b -jets.

The second region, SRB, is complementary to SRA and is designed to target the phase space of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenario with a small mass splitting between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$, referred to as the ‘compressed’ region. An initial-state radiation (ISR)-like selection is used, where the small mass splitting between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$ leads to relatively soft b -jets from the initial bottom-squark decay that are difficult to reconstruct. In this scenario it is possible to reconstruct both Higgs bosons separately by exploiting the differences in angular separation.

Finally, SRC is designed to target the compressed region of the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario, where the mass splitting between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$ is small. The b -jets from the bottom-squark decay are very soft and as such a reduced b -jet multiplicity is required in this region when compared to the A- and B-type selections. Additionally, the visible system, comprising of the b -jets from the bottom-squark decays and Higgs boson decays, is produced back-to-back with the reconstructed $\mathbf{p}_T^{\text{miss}}$.

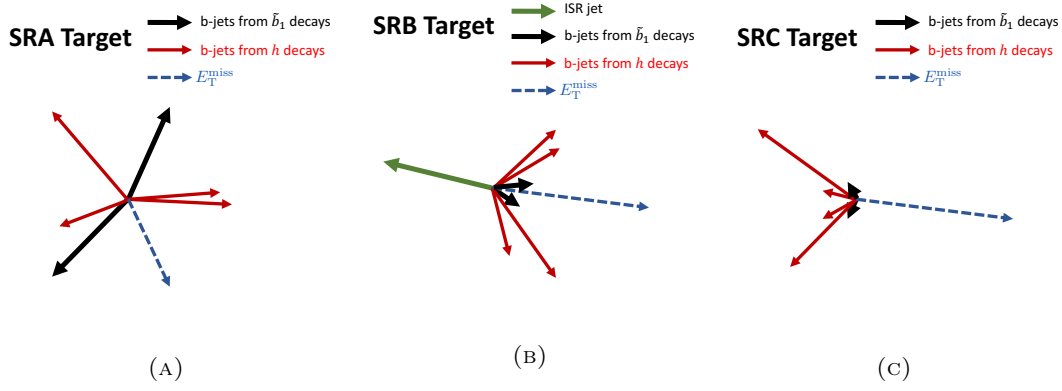


FIGURE 4.5: The different event kinematics, in the transverse plane, targeted by the three SRs: (a) kinematics in the bulk region, with high- p_T b -jets arising from the bottom-squark decay; (b) kinematics in the compressed region of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenario with soft b -jets from the bottom-squarks; (c) kinematics in the compressed region of the $m(\tilde{\chi}_1^0) = 60$ GeV scenario which also contains soft b -jets from the bottom-squarks.

Kinematic Distribution Studies

A comparison between data and MC simulation is performed for the main observables across the analysis. Three preselections are applied to the regions and are defined in Table 4.5. Full region definitions are based on these preliminary selections, where full definitions follow in Sections 4.6 and 4.7.

Variable	0-Lepton	1-Lepton	2-lepton
E_T^{miss} Trigger	✓	✓	-
Lepton Trigger			✓
N_{leptons} (baseline)	0	1	2
N_{leptons} (signal)	-	1	2 (SF, OS)
E_T^{miss} [GeV]	> 250		-
$\tilde{E}_T^{\text{miss}}$ [GeV]	-		> 250
N_{jets}	≥ 4		
$n_{b\text{-jets}}$	≥ 2	≥ 3	
$\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})]$ [rad]	> 0.4	-	> 0.2
$p_T(\ell_1)$ [GeV]	-	> 20	> 27
$p_T(\ell_2)$ [GeV]	-	-	> 20
m_T [GeV]	-	> 20	-

TABLE 4.5: Definition of the three preselection regions. Two same flavour (SF), opposite sign (OS) leptons are required in the 2-lepton preselection.

The agreement between data and MC simulations as a function of key variables is shown. Figures 4.6, 4.7, 4.8 and 4.9 present the E_T^{miss} , m_{eff} , leading b -jet p_T and the object based E_T^{miss} -significance ($\mathcal{S}$) distributions respectively for events that pass the zero-lepton preselection requirements. Figures 4.10 and 4.11 present the jet and b -jet multiplicity distributions respectively for events that pass the one-lepton preselection requirements. Figures 4.12 and 4.13 present the leading lepton p_T and invariant mass of the two leptons ($m_{\ell\ell}$) distributions respectively for events that pass the two-lepton preselection requirements. The distributions presented in Figures 4.6 and 4.9 are blinded from a suitable threshold onwards so as to not present the results in the SRs prematurely.

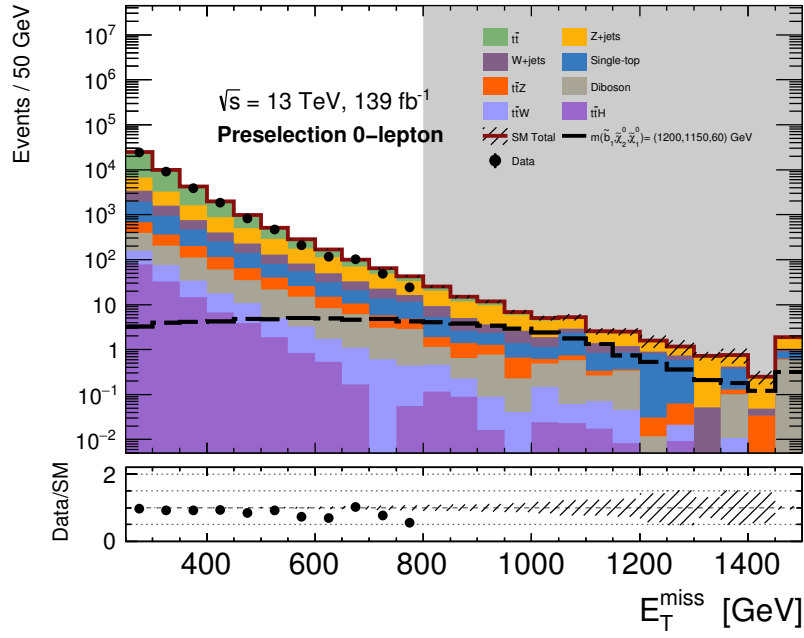


FIGURE 4.6: Distribution of E_T^{miss} for events satisfying the zero-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

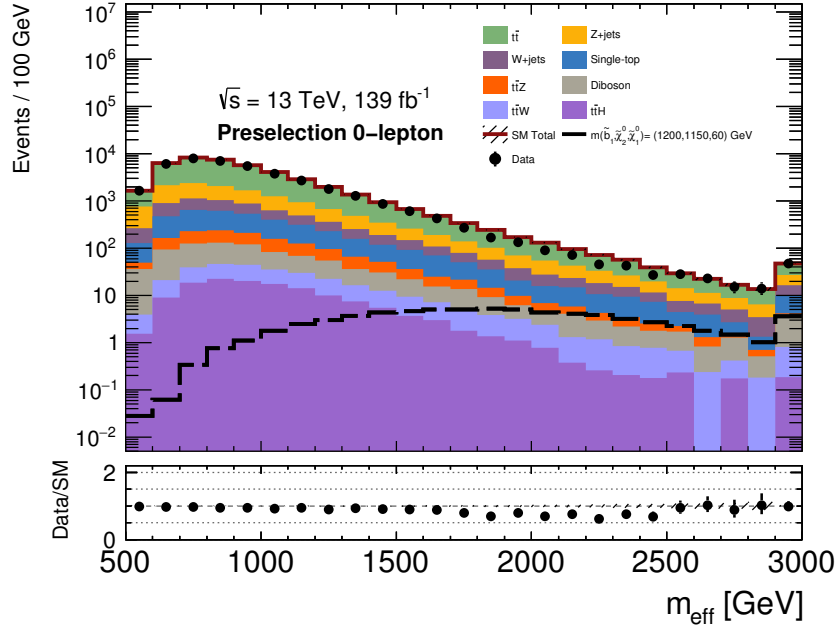


FIGURE 4.7: Distribution of m_{eff} for events satisfying the zero-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

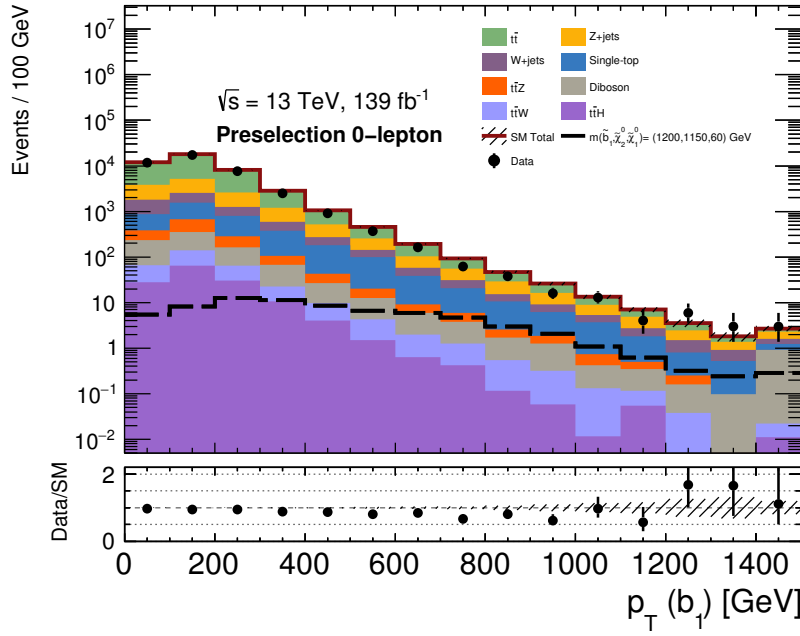


FIGURE 4.8: Distribution of leading b -jet p_T for events satisfying the zero-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

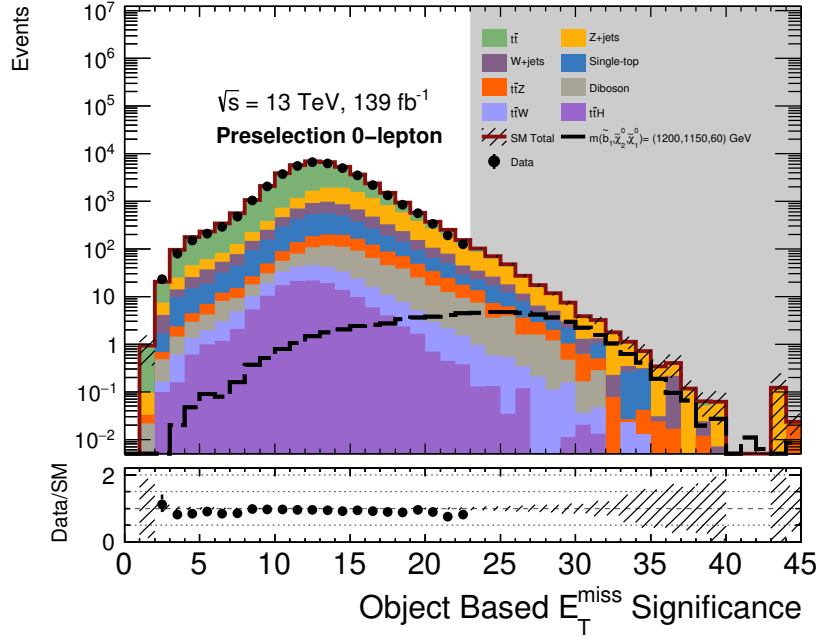


FIGURE 4.9: Distribution of object-based E_T^{miss} -significance (S) for events satisfying the zero-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

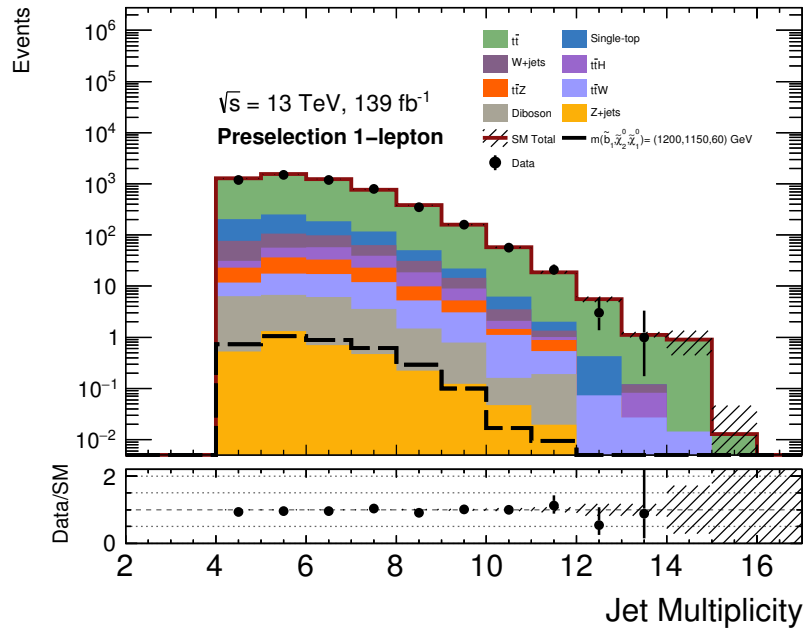


FIGURE 4.10: Distribution of jet multiplicity for events satisfying the one-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

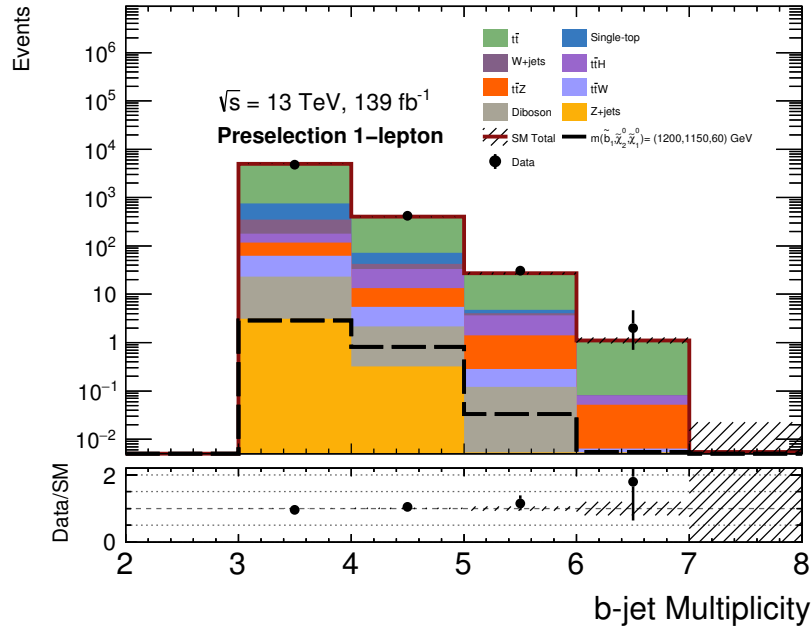


FIGURE 4.11: Distribution of b -jet multiplicity for events satisfying the one-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

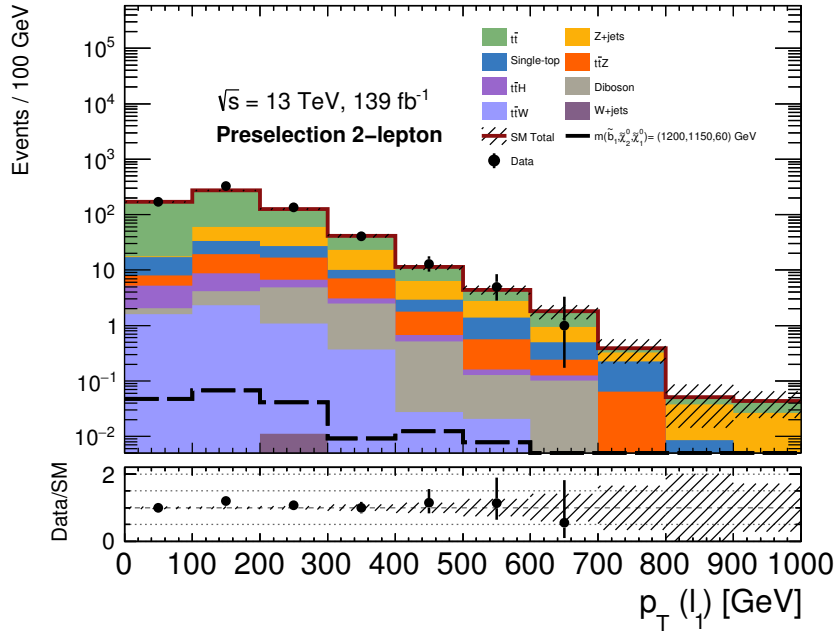


FIGURE 4.12: Distribution of leading lepton p_T for events satisfying the two-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

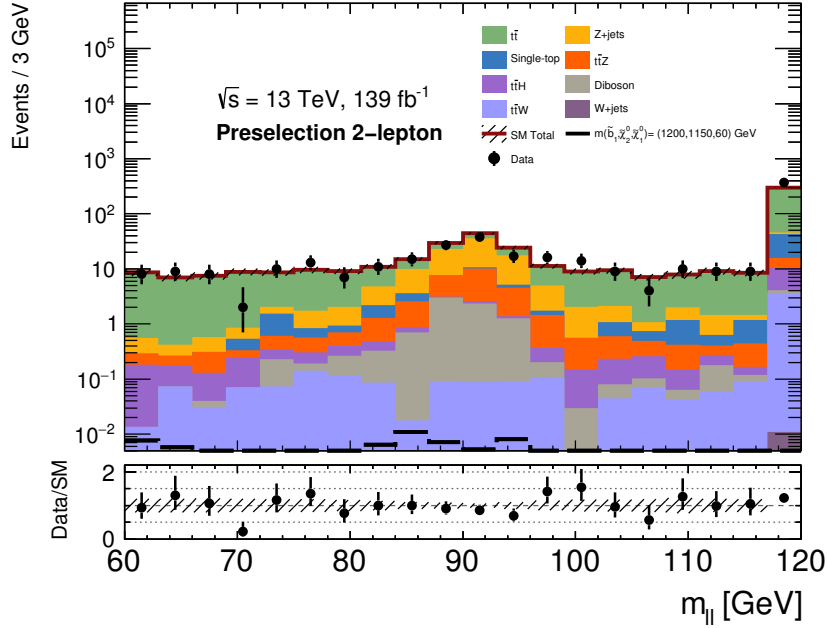


FIGURE 4.13: Distribution of the invariant mass of the two leptons ($m_{\ell\ell}$) for events satisfying the two-lepton preselection criteria before the background fit. The contributions from all SM backgrounds and a representative signal model are shown. The bottom panel shows the ratio of Data to SM event yields per bin, where the shaded bands represent the total statistical and systematic uncertainty. The rightmost bin includes overflow events.

4.5 Hypothesis Testing

Hypothesis testing is a fundamental concept in modern particle physics. It provides the statistical foundation on which its analysis is built. A common application is in quantifying the ability in distinguishing between two hypotheses, for example, the SM and supersymmetry. The method of statistical significance is used to exclude event data points and allow rejection of the SM hypothesis. Intuitively, a statistically significant observation is one that has observed a phenomenon whose interpretation allows for rejection of a given hypothesis, usually allowing for acceptance of an alternate hypothesis. This method provides a statistically consistent framework on which the analysis presented relies and implements the method in Ref. [191].

The analysis method is to take measurements of a test statistic, x , which will return a value: the number of events that pass a given variable selection. This random statistic will provide a discrimination between the two hypotheses, H_0 and H_1 - representing the SM and supersymmetry hypotheses respectively. Each variable distribution of both of the hypotheses can be described by a probability density function, given by $f_0(x)$ and $f_1(x)$ respectively.

Prior to making a measurement of the x statistic, a critical region, R , needs to be identified, such that if x was an element of the set described by the critical region, i.e. $x \in R$, then H_1 is selected and H_0 otherwise [192]. Then the formal definition of significance is the probability of $x \in R$, and selecting hypothesis H_1 , whereas H_0 is actually correct. In other words, the probability of incorrectly rejecting the hypothesis H_0 . This probability is given by,

$$\int_{x \in R} f_0(x) dx = S \quad (4.2)$$

Where S is the statistical significance.

Suppose now that an initial observation of the test statistic, x , is made and defined as x_0 ; representing the number of events for a given selection threshold. As before, the hypothesis H_0 has a probability density function $f_0(x)$, given that H_0 is true. Measurements of x at values greater than x_0 will be less consistent with H_0 i.e. less probable to appear given that H_0 is true, and that the critical region is defined as $x \geq x_0$. Therefore, the probability of measuring x larger than x_0 is given by:

$$\int_{x \geq x_0} f_0(x) dx$$

This is identical in form to Equation 4.2. It is more commonly known as the p -value of the observation and corresponds to the statistical significance of the result. It is a measure of how inconsistent a measurement is from the hypothesis. A small p -value corresponds to a strong case that the hypothesis (supersymmetry) is true, i.e. that the known and accepted null hypothesis (SM) should be rejected. In particle physics, the p -value is widely accepted as the tool in determining the ability of an experiment to distinguish between known and accepted physics from new exotic phenomena. In experimental design, the selection of the critical region, governed by the test statistic x_0 is of grave importance. Ideally a test statistic is chosen that minimises the p -value i.e. minimising the probability of incorrectly rejecting the null hypothesis.

The p -value typically can span several orders of magnitude and so it is intuitive to translate this into a ‘ z -value’, often labelled as Z , which is the deviation at the right of the mean of a Gaussian distribution, expressed in units of standard deviations, which would correspond to the same p -value [191]. The equation relating these two quantities is given by:

$$p\text{-value} = \int_{z\text{-value}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx, \quad (4.3)$$

where a z -value of 1σ corresponds to a p -value of 0.341. In particle physics an observation with a p -value = 0.0013, namely a 3σ excess, is regarded as evidence. It is common practice in the field that the stringent requirement of 5σ (p -value = 2.87×10^{-7}) is known as a discovery. This says that if an observation is made with an excess of 5σ , the probability that it is a consequence of the accepted hypothesis is 0.00003%. This is defined as the mandatory sensitivity of the observation for a discovery to be accepted.

The common particle physics experiment involving searches for a new phenomenon amongst a background process can usually reduce to that of a counting experiment. As a consequence, the probability density function describing the SM hypothesis can be modelled as a Poisson distribution. If $B \in \mathbb{R}$ events are expected, the probability of observing $D \in \mathbb{N}$ events is given by:

$$P(D|B) = \text{Poi}(D|B) = \frac{B^D}{D!} e^{-B} \quad (4.4)$$

In a Poisson model, the statistical significance can be calculated as:

$$p\text{-value} = \begin{cases} \sum_{n=D}^{\infty} \frac{B^n}{n!} e^{-B} = 1 - \sum_{n=0}^{D-1} \frac{B^n}{n!} e^{-B} & , \text{ with } D > B \\ \sum_{n=0}^D \frac{B^n}{n!} e^{-B} & , \text{ with } D \leq B \end{cases} \quad (4.5)$$

This method closely follow Ref. [191] and allows for the critical region definition to be optimised in order to maximise the statistical significance before a measurement is taken, and quantifies the validity of rejecting a hypothesis to accept another one. The underlying optimisation procedure of the presented analysis was performed to produce a final set of SR definitions attempting to maximise the statistical significance. The stringent requirement of 5σ as a discovery threshold provides a solid foundation in modern particle physics experiments, and produces results with large associated confidence levels.

4.6 Signal Region Definitions

SRA Selections

The targeted signal topology is expected to exhibit large mass differences between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$. This large mass difference leads to high p_T b -jets from the $\tilde{b}_1$ decay. In addition, the b -jets arising from the Higgs boson decay are also expected to be of relatively high p_T . Hence, the large expected E_T^{miss} from the undetectable neutralinos along with many high p_T b -jets indicates large expected m_{eff} in these events and is hence a crucial variable. In order to effectively identify signal events over a large range of $\tilde{b}_1$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses, incremental thresholds are imposed on the main discriminating variable, m_{eff} , resulting in three mutually exclusive regions, $1.0 < m_{\text{eff}} < 1.5$ TeV, $1.5 < m_{\text{eff}} < 2.0$ TeV and $m_{\text{eff}} > 2.0$ TeV. These are labelled as SRA-L, -M and -H, respectively referring to low, medium and high m_{eff} regions, to maximise coverage across the $\tilde{b}_1$ mass range. The selection criteria for the three SRAs are summarised in Table 4.6.

At least four b -tagged jets are required in the event selection. To discriminate against multijet background, events where the $\mathbf{p}_T^{\text{miss}}$ is aligned with a jet in the transverse plane are rejected by requiring

$\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})] > 0.4$. Since large E_T^{miss} is expected from the neutralinos that escape the detector, a selection of $E_T^{\text{miss}} > 350$ GeV is implemented. Additionally, the leading b -jet (b_1) is expected to have a large p_T and hence a selection of $p_T(b_1) > 200$ GeV is utilised.

At least one of the two Higgs boson candidates in the event is identified using a reconstruction algorithm referred to as the *max-min* algorithm, which is a two-step procedure designed to identify and remove the high- p_T b -jets from the bottom-squark decay and then reconstruct a Higgs boson by iterating through the remaining b -jets. The procedure is implemented as follows: firstly, pairs of b -jets are formed by iterating through all of the b -jets in the event and the pair with the largest separation in $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ is identified as originating from the initial bottom-squark decay and removed from the subsequent step; secondly, the pair from the remaining b -jets with the smallest ΔR is identified as a possible Higgs boson candidate, from which the invariant mass is calculated. This algorithm provides a few key variables, related to the ΔR and mass quantities, which provide the basis for the definition of the SR and are defined as:

- $\Delta R_{\text{max}}(b, b)$: the distance in η - ϕ between the two b -jets with the maximal angular separation which are most likely to originate from the initial decay of the $\tilde{b}_1$.
- $\Delta R_{\text{max-min}}(b, b)$: the distance in η - ϕ between the two b -jets with the minimum angular separation which are most likely to originate from the same Higgs boson decay, selected out of the remaining b -jets.
- $m(h_{\text{cand}})$: the invariant mass of the b -jet pair identified as a Higgs candidate by the *max-min* algorithm. A lower bound on $m(h_{\text{cand}})$ is used; in the majority of events the distribution peaks around the Higgs boson mass, but in scenarios where the incorrect combination of b -jets is chosen the signal can extend to higher masses.

When applied to signal events, the *max-min* algorithm correctly selects a $h \rightarrow bb$ pairing in 20%–40% of cases for a single Higgs boson decay, depending upon the signal model. For a signal model corresponding to $m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 330, 200)$ GeV, approximately 3% of the simulated signal events are identified by the SRA selections.

Variable	SRA	SRA-L	SRA-M	SRA-H
N_{leptons} (baseline)	= 0		= 0	
N_{jets}	≥ 6		≥ 6	
$n_{b\text{-jets}}$	≥ 4		≥ 4	
E_T^{miss} [GeV]	> 350		> 350	
$\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})]$ [rad]	> 0.4		> 0.4	
τ veto	Yes		Yes	
$p_T(b_1)$ [GeV]	> 200		> 200	
$\Delta R_{\text{max}}(b, b)$	> 2.5		> 2.5	
$\Delta R_{\text{max-min}}(b, b)$	< 2.5		< 2.5	
$m(h_{\text{cand}})$ [GeV]	> 80		> 80	
m_{eff} [TeV]	> 1.0	$\in [1.0, 1.5]$	$\in [1.5, 2.0]$	> 2.0

TABLE 4.6: Definitions for the SRA, alongside the three varying m_{eff} intervals used. The letter appended to the SRA label corresponds to the low (-L), medium (-M) or high (-H) m_{eff} selection. This selection is sensitive to the bulk regions of both signal scenarios. The jets and b -jets are ordered by p_T .

SRB Selections

The SRB region targets the phase space where there is small mass-splitting between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$ (of order 5–20 GeV), in the case of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenarios. As a consequence of the low mass splitting, the b -quark from the initial bottom-squark decay will be of low p_T and may not be reconstructed by the ATLAS detector. The presence of an ISR jet is utilised in this selection, whereby the ISR jet boosts the pair of bottom-squarks, and consequently their decay products are of generally higher p_T , allowing for more effective reconstruction and identification. To efficiently suppress SM background contributions, events are selected where the highest- p_T jet is not b -tagged and has $p_T > 350$ GeV. It is assumed that this jet is to have arisen from ISR in the scenario under consideration. Additional selections of $E_T^{\text{miss}} > 350$ GeV and $\Delta\phi(j_1, E_T^{\text{miss}}) > 2.8$ are applied. An m_{eff} selection of > 1 TeV is also applied. The soft p_T spectrum expected for b -jets from the $\tilde{b}_1$ decays can be detrimental to the ability to reconstruct the b -jets and hence the algorithm aiming to reconstruct the Higgs boson can no longer rely on initially removing the b -quarks from the bottom-squark decays, as in SRA. The algorithm deployed is designed to reconstruct both Higgs boson candidates.

Opposed to the scenarios targeted by SRA, pairs of b -jets with the largest ΔR are found to be more likely to arise from the decay of the same Higgs boson candidate. Two pairs at a time are identified following an iterative procedure, selecting the first pair with the largest separation in ΔR , followed by the second: ΔR_{bb1} and ΔR_{bb2} .

The average mass of the two candidates $m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ is calculated and a requirement is imposed on the average mass, corresponding to a window around the Higgs boson mass: [75, 175] GeV. For a signal model corresponding to $m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (700, 680, 550)$ GeV, about 0.1% of the simulated signal events are identified by the SRB selections. The efficiency of correctly selecting the b -jets using this algorithm is in the range 15%–30%. The SRB requirements are listed in Table 4.7.

Variable	SRB
N_{leptons} (baseline)	= 0
N_{jets}	≥ 5
$n_{b\text{-jets}}$	≥ 4
E_T^{miss} [GeV]	> 350
$\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})]$ [rad]	> 0.4
τ veto	Yes
$m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ [GeV]	$\in [75, 175]$
Leading jet not b -tagged	Yes
$p_T(j_1)$ [GeV]	> 350
$ \Delta\phi(j_1, E_T^{\text{miss}}) $ [rad]	> 2.8
m_{eff} [TeV]	> 1

TABLE 4.7: Definitions for SRB, targeting the compressed region of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenario. The jets and b -jets are ordered by p_T .

SRC Selections

In the compressed region of the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario, the ΔR based algorithms do not allow for significant discrimination between signal and background events. This is typically because the b -jets either from the $\tilde{b}_1$ decays or the Higgs decays are of low p_T , hence requirements on b -jet multiplicity as well as the reconstruction algorithms are not effective. Even if there is sufficient energy to produce b -jets from the Higgs decays then the $\tilde{\chi}_1^0$ becomes soft and hence there is low E_T^{miss} in the event. In the inclusive C-type SR, it is observed that the most powerful discriminating quantity becomes the $\mathcal{S}$, whereby a selection of $\mathcal{S} > 22$ is utilised.

Four non-overlapping regions (SRC22, SRC24, SRC26 and SRC28) are defined as subsets of the inclusive C-type SR, with incremental thresholds on $\mathcal{S}$ used as is detailed in Table 4.8, to ensure full coverage of the target models as a function of bottom-squark and neutralino mass. Events are also required to have at least three b -jets. For a signal model corresponding to $m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1200, 1150, 60)$ GeV, about 11% of the simulated signal events are identified by the SRC selections. The $\mathcal{S}$ variable is effective in rejecting the SM background arising from associated production of a Z boson decaying into neutrinos and b -jets.

Variable		SRC	SRC22	SRC24	SRC26	SRC28
N_{leptons} (baseline)		= 0		= 0		
N_{jets}		≥ 4		≥ 4		
$n_{b\text{-jets}}$		≥ 3		≥ 3		
$E_{\text{T}}^{\text{miss}}$	[GeV]	> 250		> 250		
$\min[\Delta\phi(\text{jet}_{1-4}, E_{\text{T}}^{\text{miss}})]$	[rad]	> 0.4		> 0.4		
$\mathcal{S}$		> 22	$\in [22, 24]$	$\in [24, 26]$	$\in [26, 28]$	> 28

TABLE 4.8: Definitions for SRC, alongside the four varying $\mathcal{S}$ intervals used. The number appended to the SRC label corresponds to the lower bound on the $\mathcal{S}$ interval. SRC targets small mass splittings between the $\tilde{b}_1$ and $\tilde{\chi}_2^0$, in the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario. The jets and b -jets are ordered by p_{T} .

4.7 Background Estimation

There are two main SM backgrounds that are expected to contribute to the event yields in the SRs. For SRAs and SRB, the main background is top production which, according to MC estimates, contributes between 70% and 85% of the total background, depending upon the region considered, and is dominated by top-quark pairs produced in association with two b -quarks arising from gluon splitting. In the SRCs, the main backgrounds arise from Z +jets (up to 50% of the total) and from top-quark-related processes (up to 20% of the total). The contribution of background processes is estimated in designated CRs and verified in associated VRs. The CRs are designed to be enriched in specific background contributions relevant to the analysis, whilst minimising the potential signal contamination. They are also orthogonal to the SRs. The remaining background processes, namely W +jets, $t\bar{t} + W/Z/h$ and diboson are found to contribute minimally and are henceforth combined and labelled as ‘Other’.

The contribution of each background process is determined using a semi-data driven technique, whereby normalisation factors are calculated by fitting the estimated number of MC events to the observed number of data events within a designated CR. The reliability of the MC extrapolation of the SM background estimates outside of the CRs is evaluated in dedicated VRs, orthogonal to CRs and SRs. The normalisation factor determined in the CR is referred to as the μ -factor. From the calculated μ -factor, Transfer Factors (TFs) for each normalised background process, i , can be obtained, which convert the observed number of events in each CR to an estimated number of background events in the SRs. The TFs and the μ -factor can be determined using Equations 4.6 and 4.7 respectively:

$$N_{i,SR}^{\text{exp}} = \left(\frac{N_{i,SR}^{\text{MC}}}{N_{i,CR}^{\text{MC}}} \right) \cdot N_{i,CR}^{\text{obs}} \quad (4.6)$$

$$= \mu_i \cdot N_{i,SR}^{\text{MC}} \quad (4.7)$$

The factor in braces in Equation 4.6 is the TF, where $N_{i,SR}^{MC}$ is the number of expected MC events for a given background process in the SR, and $N_{i,CR}^{MC}$ is analogous for the CR. The μ_i term is the associated μ -factor for background process i . Crucially, with the use of TFs (and μ -factors), systematic uncertainties on the background processes can be significantly reduced through cancellation if there is little extrapolation between a CR and a VR/SR. It is therefore favourable to define all of the regions to be as kinematically close as possible, while still ensuring orthogonality.

The fitting procedure used in the analysis is implemented using the HistFitter [193] framework. The main SM backgrounds in each SR are determined separately with a profile likelihood fit to the event yields in the associated CRs [194]. The likelihood fit takes as input: the number of expected MC events for each process, in each CR and SR; the number of observed data events in each region; and the errors on the number of expected MC events arising from the systematic uncertainties. The background processes that do not have an associated CR are not normalised to data but their normalisation is taken from theoretical calculations. When the fit is performed these non-fitted background samples are allowed to float within their own uncertainties during the fit.

A likelihood function, $\mathcal{L}$, is built using the products of the Poisson distributions of the number of events (MC and observed) in each of the SRs, P_{SR} , and CRs, P_{CR} , and additional distributions to implement the systematic uncertainties, C_{syst} , as:

$$\mathcal{L}(n, \theta^0 | \mu_{sig}, b, \theta) = P_{SR} \times P_{CR} \times C_{syst} \quad (4.8)$$

$$= P(n_s | \lambda_s(\mu_{sig}, b, \theta)) \times \left(\prod_{i \in CR} P(n_i | \lambda_i(\mu_{sig}, b, \theta)) \right) \times C_{syst}(\theta^0, \theta) \quad (4.9)$$

where $P(n|\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$ is a Poisson distribution describing the estimated number of events, n , given the expectation λ ; n_s is the expected number of events in each SR, and n_i is the expected number of events in each CR; λ are functions describing the number of expected events, dependent on: the background prediction, b , for the processes¹; the nuisance parameters, θ , associated with the systematic uncertainties; and finally the signal strength parameter, μ_{sig} , which can be set to zero or to one, to either include or remove the signal component in the fit.

The systematic term, $C_{syst}(\theta^0, \theta)$, is a probability density function that models the systematic uncertainties described in Section 4.8 and are introduced in the fit as nuisance parameters. They are constrained by Gaussian distributions centred at zero, θ^0 , around which the nominal value, θ , can vary, where the widths correspond to the size of the uncertainties and are treated as correlated, when appropriate, between the various regions. The product of the various probability density functions and the Gaussian distributions forms the likelihood function, which the fit maximises by adjusting the background normalisation and the nuisance parameters. This approach reduces the influence of systematic uncertainties on the backgrounds with dedicated CRs, as these are absorbed by the normalisation parameter.

After the assembly of the likelihood function, there are three statistical interpretations using Equation 4.9 that are performed throughout the analysis: a background-only fit, a model-dependent fit, and a model-independent fit.

¹Implicitly contained here are the normalisation parameters μ_i .

Background-Only Fit

The background-only fit is performed to extract the normalisation parameters for each of the backgrounds that have associated CRs. The purpose of the fit is to produce an estimate of the total background expectation in the SRs (and VRs) without making any assumptions on the signal model under consideration ($\mu_{\text{sig}} = 0$).

The background-only fit uses the observed event yield and the expected number of MC events in the associated CRs as a constraint to adjust the normalisation of the background processes, assuming that no signal is present. The information from the VRs and SRs is removed prior to the fit. These normalisation parameters are then introduced into a different likelihood function, containing information from the CRs, VRs and SRs, to produce estimates of the number of background events in the SRs and VRs.

When performing the fit for SRA, a multi-bin approach is used, with a single CR divided into three bins of m_{eff} . Such an approach allows for the calculation and use of a single normalisation parameter (applied to the main $t\bar{t}$ background across all bins of m_{eff}), and additionally enables the fit to take into account the modelling of the m_{eff} variable. This single normalisation factor represents the best fit amongst the CR bins, while its systematic uncertainties are constrained across the CR bins.

Model-Dependent Fit

The model dependent fit, also known as an ‘exclusion’ fit, is a frequentist fit performed intending to study a specific signal model. It is also referred to as an exclusion fit because if there is no significant excess of events in the SRs (which is known by previously performing the background-only fit), then exclusion limits can be placed on a specific signal model considered. In the case of an excess, then the model-dependent fit can be used to measure the signal strength of the model.

In this scenario, the likelihood function is built and the signal model under investigation is included in the fit for all CRs and SRs. From this the normalisation parameter/signal strength (μ_{sig}) is calculated for the signal model. Usually when performing an exclusion fit, a grid of signal samples with different mass assumptions are used, where a fit is performed individually on each signal sample of the grid. The results of the exclusion fit, when taking into account all of the signal mass scenarios, allow an exclusion contour to be placed in the mass plane considered (for this analysis, in the $\tilde{b}_1, \tilde{\chi}_2^0$ mass plane).

To construct an exclusion contour, each signal model hypothesis test is individually considered. The signal strength is used as the parameter of interest in the test. The model can be considered to be excluded at the 95% Confidence Level (CL) [195], if the results of the hypothesis test return a p -value of < 0.05 . In this context the p -value is the probability of rejecting the signal plus background hypothesis.

Model-Independent Fit

The so-called ‘discovery’ fit provides a model-independent limit on any additional number of events in the SRs beyond the expected number of background events. This enables the results of the analysis to be interpreted in the context of any generic model, not specifically supersymmetry, which would expect to contribute to the expected number of events in the SRs.

The procedure for this fit follows the general scheme of the model-dependent fit, however a ‘dummy’ signal is inserted instead of using a defined signal model. In this scenario no signal

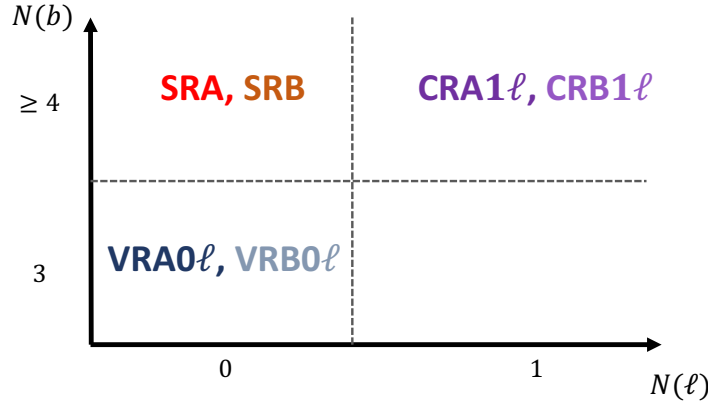


FIGURE 4.14: Schematic diagram of the fit strategies for the A-, B-type regions. The CRs require a different lepton multiplicity to the SRs, whilst the VRs are defined with a lower b -jet multiplicity.

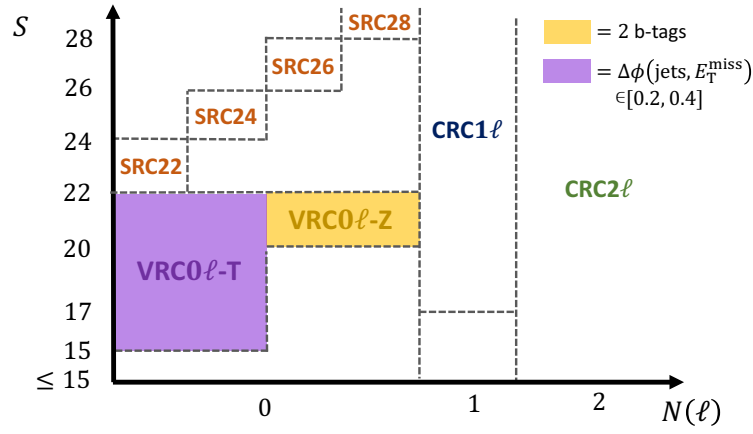


FIGURE 4.15: Schematic diagram of the fit strategies for the C-type regions. The CRs generally require a different lepton multiplicity to the SRs, whilst the VRs are defined with a lower b -jet multiplicity, except in the case of the VRC0l-T region, which instead inverts the SR $\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})]$ selection.

contamination is taken into account in the CRs ($\mu_{\text{sig}} = 0$). The number of observed events in the SR is added to the fit to enable the signal strength (of the dummy signal) to be investigated. The value of the signal strength where the CLs value falls below the 5% level (corresponding to a p -value of 0.05) is finally evaluated, which can then be converted into an upper limit on the visible cross-section of a generic BSM production mechanism, σ_{vis} , which is defined as the product of the cross-section for the process, the selection efficiency and the detector acceptance.

The fit strategies for the A- and B-type regions are very similar and are represented schematically in Figure 4.14, depicting how orthogonality between the various regions is achieved. They rely on CRs with a single-lepton requirement, since the $t\bar{t}$ background in the SR is dominated by semileptonic $t\bar{t}$ decays where the lepton is not identified. The main background in both regions is $t\bar{t}$ pair production in association with heavy-flavour jets. The fit strategy for the C-type regions is presented in Figure 4.15. Since the main background in these regions is different to that expected in the A- and B-type regions, the strategy is redesigned in order to perform optimally, where these regions are dominated by Z +jets, closely followed by the top-quark backgrounds.

In order to define CRs enhanced in $t\bar{t}$ and Z +jets, additional variables are used:

- m_T : the event transverse mass m_T is defined as $m_T = \sqrt{2p_T(\ell)E_T^{\text{miss}}(1 - \cos(\Delta\phi))}$, where $\Delta\phi$ is the difference in azimuthal angle between the lepton and the $\mathbf{p}_T^{\text{miss}}$. This is used in the one-lepton CRs to reject multijet events that can be misidentified as containing a lepton.
- $m_{\ell\ell}$: the invariant mass of the two leptons in the event. Since the two-lepton CR is used to constrain the Z +jets background, the $m_{\ell\ell}$ variable is required to be within the Z -mass window: [86, 106] GeV (used exclusively in the two-lepton CR).
- $\tilde{E}_T^{\text{miss}}$: the ‘lepton corrected’ E_T^{miss} . For the two-lepton CR the transverse momentum vectors of the leptons are subtracted from the E_T^{miss} calculation in order to mimic the neutrinos from $Z \rightarrow \nu\nu$ decays (used exclusively in the two-lepton CR).

When designing the CRs and VRs, the potential signal contamination is checked in each of the regions to ensure that the selections imposed minimally reduces the contribution from the signal process. The signal contamination in the CRs and VRs is found to be negligible, at the level of $< 1\%$ of the total SM expectation, depending upon the signal mass hierarchy of the models considered in this search.

A-Type Control and Validation Region Definitions

A $t\bar{t}$ -dominated CR, CRA1 ℓ , is defined for the A-type regions and is split in order to mimic the m_{eff} selections of the SRAs. The CR is defined similarly to the SR selection, however, exactly one signal lepton, either e or μ , with $p_T > 20$ GeV is required in the final state. Additionally, the selections that are designed to isolate the Higgs boson in the SRAs, namely the selections on the $\Delta R_{\text{max}}(b, b)$, $\Delta R_{\text{max-min}}(b, b)$ and $m(h_{\text{cand}})$ variables, are not applied in order to increase the number of events in the CR. The leading b -jet p_T selection is lowered to > 100 GeV to further increase the number of events, whilst a selection on the transverse mass of $m_T > 20$ GeV is applied to reject events with misidentified leptons. These selections produce pure $t\bar{t}$ CRs, with $t\bar{t}$ accounting for more than 80% of the total in each of the CRs. The fraction of top-quark pairs produced in association with b -quarks is equivalent between both the CRs and SRs, and accounts for about 70% of the total $t\bar{t}$ background.

A zero-lepton validation region, VRA0 ℓ , is also defined and follows the same selection thresholds in m_{eff} as in the SRAs and CRAs. This VR is used to validate the modelling of the $t\bar{t}$ background when extrapolating from the one-lepton CRs to the zero-lepton regions. The selections are based mostly on the SR selections, but they are orthogonal due to the b -jet multiplicity selection, which requires exactly three b -jets. Additionally, the $\Delta R_{\text{max}}(b, b)$, $\Delta R_{\text{max-min}}(b, b)$ and $m(h_{\text{cand}})$ selections are not applied. A selection of $\mathcal{S} < 22$ is applied to ensure this region is orthogonal to the SRC regions.

The expected pre-fit yields and the observed number of data events in CRA1 ℓ are presented in Table 4.9. Full definitions of the A-Type CR and VR can be found in Table 4.13. Figure 4.16 presents the post-fit distribution of $m(h_{\text{cand}})$ in CRA1 ℓ and shows that the variable is well modelled.

B-Type Control and Validation Region Definitions

For the B-type $t\bar{t}$ CR, CRB1 ℓ , a similar scheme of utilising a one-lepton region enriched in $t\bar{t}$ is used. The selections are based mostly on the SR selections, with an additional selection requiring

Observed events	224		
MC exp. SM events	231.51	$\pm$	3.88
$t\bar{t}$	189.87	$\pm$	3.07
Z +jets	0.27	$\pm$	0.12
Single-top	14.76	$\pm$	1.95
$t\bar{t} + W/Z$	7.36	$\pm$	0.76
$t\bar{t} + h$	12.11	$\pm$	0.56
W +jets	5.98	$\pm$	0.98
Diboson	1.25	$\pm$	0.46

TABLE 4.9: Expected pre-fit CRA1 ℓ yields including the observed number of data events.

exactly one signal lepton with $p_T > 20$ GeV. The $m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ selection is removed in order to increase the number of events in the region, and the $|\Delta\phi(j_1, E_T^{\text{miss}})|$ selection is loosened to > 2.2 . Similarly to the A-type CR, a selection of $m_T > 20$ GeV is applied to suppress misidentified leptons. These selections produce a pure $t\bar{t}$ CR, dominating 80% of the total expected SM background.

The associated VR, VRB0 ℓ , is defined using a similar technique to that of the A-type VR, with selections similar to those of the SRB region, but also includes an exclusive b -jet multiplicity selection of exactly three b -jets. Additionally, the selections used to reconstruct the Higgs bosons in the event are removed in order to increase the number of events in the region. A selection of $\mathcal{S} < 22$ is also applied to ensure this region is orthogonal to the C-type SRs.

The expected pre-fit yields and the observed number of data events in CRB1 ℓ are presented in Table 4.10. Full definitions of the B-Type CR and VR can be found in Table 4.13. Figure 4.17 presents the post-fit distribution of $m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ in CRB1 ℓ and shows that the variable is well modelled.

Observed events	42		
MC exp. SM events	43.49	$\pm$	1.21
$t\bar{t}$	37.80	$\pm$	0.86
Z +jets	0.11	$\pm$	0.11
Single-top	2.08	$\pm$	0.74
$t\bar{t} + W/Z$	1.06	$\pm$	0.31
$t\bar{t} + h$	1.41	$\pm$	0.21
W +jets	0.85	$\pm$	0.21
Diboson	0.23	$\pm$	0.11

TABLE 4.10: Expected pre-fit CRB1 ℓ yields including the observed number of data events.

C-Type Control and Validation Region Definitions

Two complementary CRs are defined for the C-type SRs: one to model the Z +jets background, CRC2 ℓ , and one to model the backgrounds associated with top-quarks, $t\bar{t}$ and single top, CRC1 ℓ . A single normalisation parameter is used to constrain both the $t\bar{t}$ and single-top backgrounds, while the Z +jets background is constrained with its own dedicated normalisation parameter. These CRs are based upon the C-type SRs, but are orthogonal due to their differing lepton multiplicity requirements.

The CRC2 ℓ requires two same-flavour (SF) and opposite-sign (OS) leptons, with an invariant mass in the Z boson mass window. The two highest p_T leptons are required to have $p_T > 27$ GeV

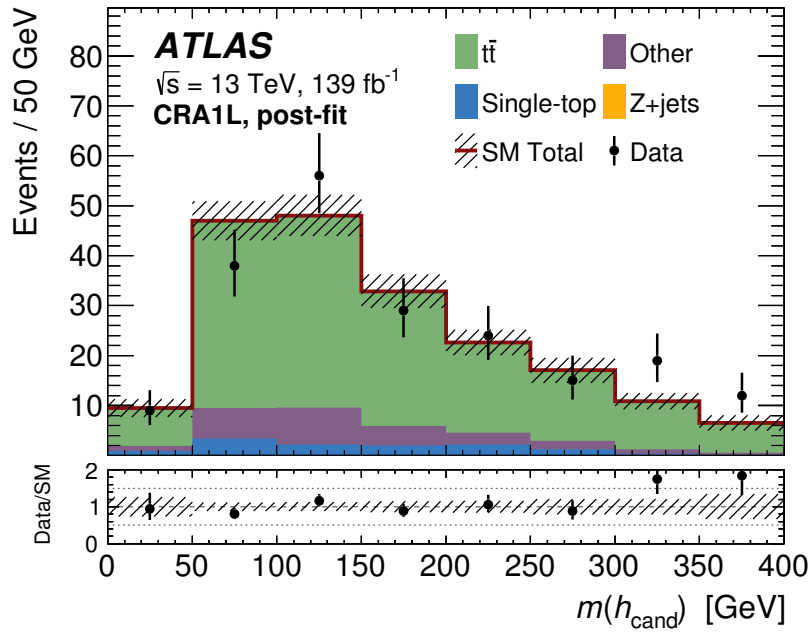


FIGURE 4.16: Distribution of $m(h_{\text{cand}})$ in CRA1 ℓ after the background-only fit; ratios of data to SM predictions are reported in the bottom panel. All uncertainties as defined in Section 4.8 are included in the uncertainty bands of the top and bottom panels in each plot. The backgrounds which contribute only a small amount (diboson, W +jets and $t\bar{t} + W/Z/h$) are grouped and labelled as ‘Other’. Overflow events that do not fall into the axis range are placed into the rightmost bin.

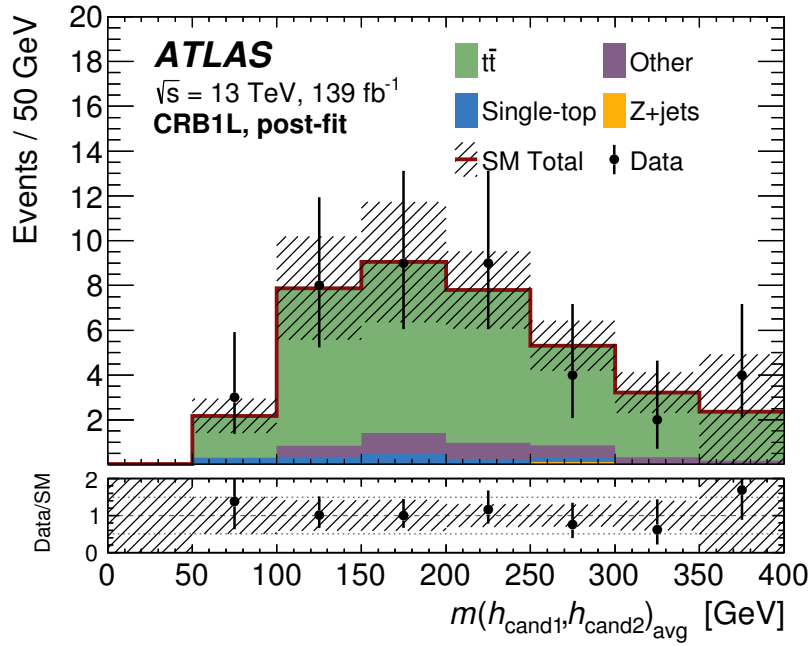


FIGURE 4.17: Distribution of $m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$ in CRB1 ℓ after the background-only fit; ratios of data to SM predictions are reported in the bottom panel. All uncertainties as defined in Section 4.8 are included in the uncertainty bands of the top and bottom panels in each plot. The backgrounds that contribute only a small amount (diboson, W +jets and $t\bar{t} + W/Z/h$) are grouped and labelled as ‘Other’. Overflow events that do not fall into the axis range are placed into the rightmost bin.

and $p_T > 20$ GeV respectively. In order to imitate the E_T^{miss} selection in the SR, a selection of $\tilde{E}_T^{\text{miss}} > 250$ GeV is utilised. For this region the selections on $\mathcal{S}$ are removed in order to increase the number of events in the region. The CRC1 ℓ region used to constrain the top-quark related backgrounds requires one signal lepton with $p_T > 20$ GeV. A selection of $\mathcal{S} > 17$ is also applied. Similarly to the A- and B-type CRs, a selection of $m_T > 20$ GeV is applied to suppress the multijet contribution from fake or misidentified leptons.

Two zero-lepton VRs are defined to validate the extrapolation from CR to SR based on the SR selections. A VR with zero-leptons and two b -jets is defined, VRC0 ℓ -Z, with $\mathcal{S} \in [20, 22]$ and $E_T^{\text{miss}} \in [250, 600]$ GeV ensuring orthogonality to the SR, while enhancing the contribution from the Z +jets process. A second VR is used to validate the modelling of the $t\bar{t}$ and single-top backgrounds, VRC0 ℓ -T, defined with a selection of zero-leptons, $\mathcal{S} \in [15, 22]$ and an inverted selection on the $\min[\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})] \in [0.2, 0.4]$ in order to ensure orthogonality.

The expected pre-fit yields and the observed number of data events in CRC1 ℓ and CRC2 ℓ are presented in Tables 4.11 and 4.12 respectively. Full definitions of the C-Type CRs and VRs can be found in Table 4.13. Figures 4.18 and 4.19 present the post-fit distributions of $\mathcal{S}$ in CRC1 ℓ and $\tilde{E}_T^{\text{miss}}$ in CRC2 ℓ respectively and show that these variables are well modelled.

A full overview of the CR and VR definitions used for the background estimation throughout the analysis can be found in Table 4.13.

Observed events	143		
MC exp. SM events	173.43	$\pm$	3.51
$t\bar{t}$	108.26	$\pm$	1.05
Z +jets	0.32	$\pm$	0.16
Single-top	30.75	$\pm$	2.81
$t\bar{t} + W/Z$	11.17	$\pm$	0.75
$t\bar{t} + h$	2.88	$\pm$	0.24
W +jets	17.26	$\pm$	1.62
Diboson	2.77	$\pm$	0.58

TABLE 4.11: Expected pre-fit CRC1 ℓ yields including the observed number of data events.

Observed events	73		
MC exp. SM events	75.37	$\pm$	2.58
$t\bar{t}$	3.09	$\pm$	0.94
Z +jets	53.18	$\pm$	1.93
Single-top	–		
$t\bar{t} + W/Z$	13.08	$\pm$	0.46
$t\bar{t} + h$	0.10	$\pm$	0.10
W +jets	–		
Diboson	5.92	$\pm$	5.92

TABLE 4.12: Expected pre-fit CRC2 ℓ yields including the observed number of data events.

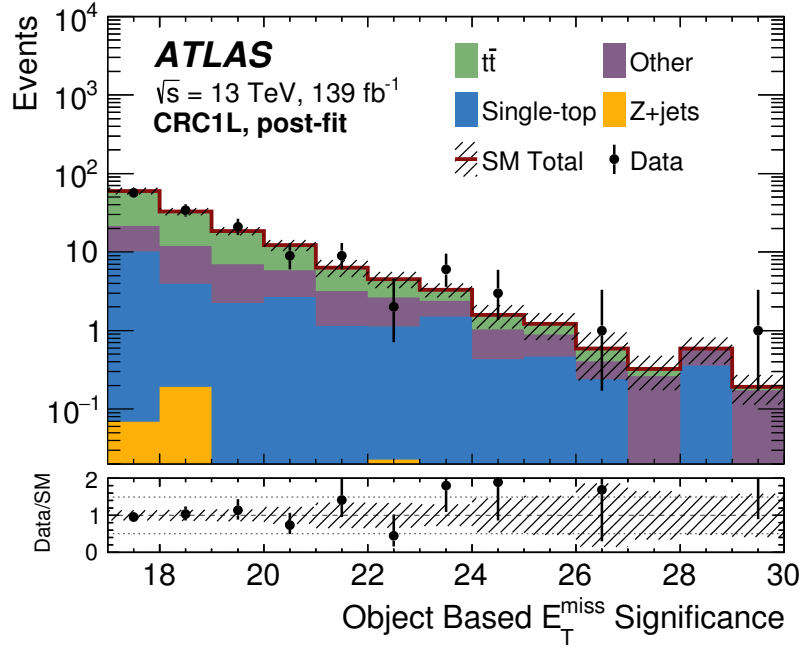


FIGURE 4.18: Distribution of S in CRC1 ℓ after the background-only fit; ratios of data to SM predictions are reported in the bottom panel. All uncertainties as defined in Section 4.8 are included in the uncertainty bands of the top and bottom panels in each plot. The backgrounds that contribute only a small amount (diboson, W +jets and $t\bar{t} + W/Z/h$) are grouped and labelled as ‘Other’. Overflow events that do not fall into the axis range are placed into the rightmost bin.

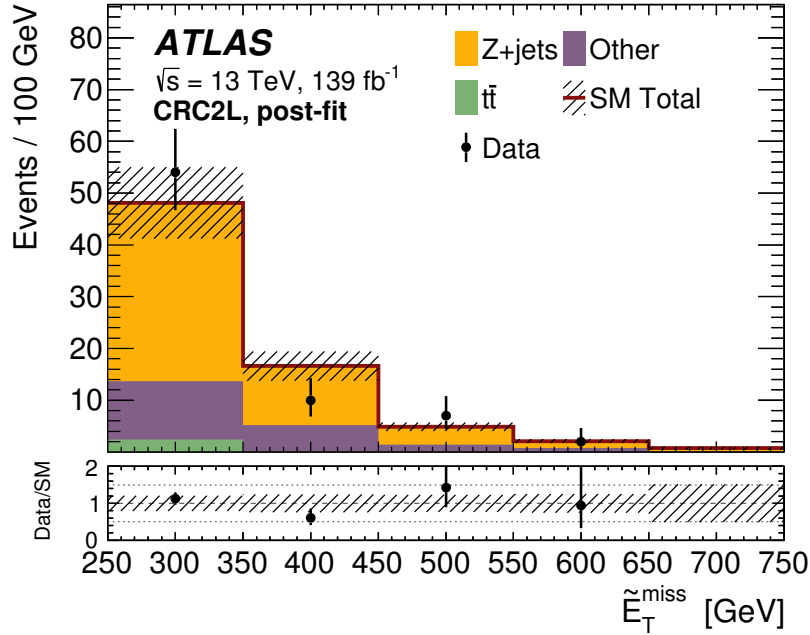


FIGURE 4.19: Distribution of $\tilde{E}_T^{\text{miss}}$ in CRC2 ℓ after the background-only fit; ratios of data to SM predictions are reported in the bottom panel. All uncertainties as defined in Section 4.8 are included in the uncertainty bands of the top and bottom panels in each plot. The backgrounds that contribute only a small amount (diboson, W +jets and $t\bar{t} + W/Z/h$) are grouped and labelled as ‘Other’. Overflow events that do not fall into the axis range are placed into the rightmost bin.

TABLE 4.13: Summary of all control and validation region definitions used for background estimation.

Variable	Units	Control Regions				Validation Regions			
		CRA1 ℓ	CRB1 ℓ	CRC1 ℓ	CRC2 ℓ	VRA0 ℓ	VRB0 ℓ	VRC0 ℓ -T	VRC0 ℓ -Z
$E_{\text{T}}^{\text{miss}}$ Trigger		✓	✓	✓	-	✓	✓	✓	✓
Lepton Trigger		-	-	-	✓	-	-	-	-
$E_{\text{T}}^{\text{miss}}$	[GeV]	> 250	> 300	> 250	< 70	> 350	> 350	> 250	$\in [250, 600]$
$\min[\Delta\phi(\text{jet}_{1-4}, E_{\text{T}}^{\text{miss}})]$	[rad]	-	-	-	> 0.2	> 0.4	> 0.4	$\in [0.2, 0.4]$	> 1.2
N_{leptons} (baseline)		= 1	= 1	= 1	= 2	= 0	= 0	= 0	= 0
N_{leptons} (signal)		= 1	= 1	= 1	= 2(SFOS)	-	-	-	-
$p_{\text{T}}(\ell_1)$	[GeV]	> 20	> 20	> 20	> 27	-	-	-	-
$p_{\text{T}}(\ell_2)$	[GeV]	-	-	-	> 20	-	-	-	-
m_{T}	[GeV]	> 20	> 20	> 20	-	-	-	-	-
$m_{\ell\ell}$	[GeV]	-	-	-	$\in [86, 106]$	-	-	-	-
τ veto		-	✓	-	-	✓	✓	-	-
N_{jets}		≥ 6	≥ 4	≥ 4	≥ 4	≥ 6	≥ 4	≥ 4	≥ 4
$n_{b\text{-jets}}$		≥ 4	≥ 4	≥ 3	≥ 3	= 3	= 3	≥ 3	= 2
$p_{\text{T}}(b_1)$	[GeV]	> 100	-	-	-	> 100	-	-	-
$p_{\text{T}}(j_1)$	[GeV]	-	> 350	-	-	-	> 350	-	-
Leading jet not b-tagged		-	✓	-	-	-	✓	-	-
$ \Delta\phi(j_1, E_{\text{T}}^{\text{miss}}) $	[rad]	-	> 2.2	-	-	-	> 2.8	-	-
$\tilde{E}_{\text{T}}^{\text{miss}}$	[GeV]	-	-	-	> 250	-	-	-	-
$\mathcal{S}$		-	-	> 17	-	< 22	< 22	$\in [15, 22]$	$\in [20, 22]$
m_{eff}	[TeV]	> 1.0	> 1.0	-	-	> 1.0	> 1.0	-	-

4.8 Systematic Uncertainties

Several sources of experimental and theoretical systematic uncertainty on the signal and background estimates are considered throughout this analysis. Experimental systematic uncertainties arise from the detector, while theoretical systematic uncertainties are from the MC modelling process. The impact of these uncertainties is reduced by fitting the event yields and normalising the dominant backgrounds in the CRs defined with kinematic selections closely following those of the corresponding SRs. Uncertainties due to the the numbers of events in the CRs are also introduced in the fit for each of the regions. The contribution of the uncertainties is categorised by the source from which they arise, either from detector, theoretical modelling or statistical uncertainties and are summarised in Table 4.14.

Dominant detector-related systematic uncertainties arise from the b -tagging efficiency and mis-tagging rates, and from the jet energy scale and resolution. The contribution of these uncertainties is nearly equivalent in SRA and SRB. In SRC, the b -tagging uncertainty is dominant.

The b -tagging uncertainty is estimated by varying the η -, p_T - and flavour-dependent scale factors applied to each jet in the simulation within a range that reflects the systematic uncertainty in the measured tagging efficiency and mis-tag rates in data [133]. The systematic uncertainty on the b -tagging efficiency ranges from 4.5% for b -jets with $p_T \in [35, 40]$ GeV up to 7.5% for b -jets with high p_T (> 100 GeV).

Since reconstructed jets are initially calibrated at the electromagnetic energy scale, a jet energy scale calibration is applied to correct for the mismeasurement in true jet energy and to account for detector effects, inefficiencies in calorimeter clustering and jet reconstruction. The uncertainties in the jet energy scale and resolution are based on their respective measurements in data [123, 126].

Estimation of the uncertainties arising from the calibration of the lepton energy scale and resolution follows a similar prescription to that of the jet energy scale/resolution. The uncertainty on the scale factors applied to MC to replicate the reconstruction, identification, isolation and trigger efficiencies are considered. The uncertainties associated with lepton reconstruction and energy measurements have a negligible impact on the final results.

Uncertainties in the E_T^{miss} calculation are propagated from the leptons, photon and jet-related uncertainties, and additional uncertainties due to the energy scale and resolution of the soft term are included in the E_T^{miss} . The systematic uncertainties related to the modelling of the energy of jets and leptons in the simulation are propagated to $\mathcal{S}$. Since the energy resolutions are taken to be the maximum of the parameterised data and simulation resolutions when performing the calculation for both data and MC, no additional uncertainty is applied.

Uncertainties in the modelling of the SM background processes from MC simulation and from their theoretical cross-section uncertainties are also considered. These uncertainties are a consequence of the choice of generator used at each stage of the MC simulation. They are calculated as the difference between the prediction of the nominal samples and from additional samples differing in hard-scattering generator and parameter settings, or by using internal weights assigned to the events depending on the choice of renormalisation and factorisation scales, initial- and final-state radiation parameters, and PDF sets.

The dominant uncertainties in SRA and SRB originate from theoretical and modelling uncertainties of the $t\bar{t}$ background. The impact of the PS and hadronisation model is determined by comparing the nominal generator with an additional POWHEG sample interfaced to HERWIG 7 [196, 197], using the H7UE set of tuned parameters [197]. To assess the uncertainty due to the choice of hard-scattering generator and matching scheme, an alternative generator setup using

aMC@NLO+PYTHIA 8 is used. It uses the shower starting scale, $\mu_q = H_T/2$, where H_T is defined as the scalar sum of the p_T of all outgoing partons.

The dominant uncertainties in SRC arise originate from the MC modelling of the Z +jets process, followed by the modelling of the $t\bar{t}$ and single-top processes. The Z +jets, as well as W +jets, modelling uncertainties are estimated by using different merging (CKKW-L) and resummation scales in alternative samples, PDF variations from the NNPDF30NNLO replicas [151], and variations of factorisation and renormalisation scales in the ME. The latter have been evaluated using 7 point-variations, changing the renormalisation and factorisation scales up and down by factors 0.5 and 2, such that when one scale is up the other is down, and vice-versa.

For the supersymmetry signal processes, both the experimental and theoretical uncertainties in the expected signal yield are taken into account. The experimental uncertainties are found to be 6–36% across the $m(\tilde{\chi}_1^0) = 60$ GeV mass eventualities for A-type SRs, and 4–40% for C-type SRs. For models where $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV is assumed, mass eventualities where SRB becomes significant have uncertainties of 11–37%.

In all SRs, the dominant uncertainty on the signal yields is found to be from the b -tagging efficiency.

Theoretical uncertainties in the approximate NNLO+NNLL cross-section are calculated for each supersymmetry signal scenario, where the uncertainties in the renormalisation and factorisation scales dominate, followed by the uncertainty in the PDFs. These are found to be 7–17% for bottom-squark masses in the range between 400 GeV and 1500 GeV. Additional uncertainties in the acceptance and efficiency due to the modelling of ISR and CKKW scale variations in supersymmetry signal MC samples are also considered, and contribute up to $\sim 10\%$.

Region	SRA		SRB		SRC	
Total background expectation	17.1		3.3		37.9	
Total background uncertainty	2.8	(16%)	0.9	(27%)	6.2	(16%)
Systematic, experimental	1.4	(8%)	0.3	(10%)	3.0	(8%)
Systematic, theoretical	2.3	(13%)	0.6	(18%)	3.2	(8%)
Statistical, MC samples	0.7	(4%)	0.4	(12%)	2.0	(5%)

TABLE 4.14: Expected background event yields and dominant systematic uncertainties on background estimates in the A-type (inclusive), B-type and C-type (inclusive) regions. Individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

4.9 Background-only Fit Results

The background-only fit results for the A- B- and C-type CRs and VRs are presented in Tables 4.15, 4.16 and 4.17 respectively. Generally a good overall agreement is found between the MC prediction and the observed data within uncertainties, where all μ -factors are consistent with unity, within 2σ of the normalisation uncertainty, suggesting that the modelling of the crucial SM background processes is already good before performing the fit. For the A-type regions, since the fit is performed in the m_{eff} intervals, the normalisation is applied to all bins equally. Table 4.18 presents the associated μ -factors to each of the regions.

	CRA1 ℓ			VRA0 ℓ		
Observed events	224			294		
Fitted SM bkg events	224.10	$\pm$	14.96	216.4	$\pm$	24.1
$t\bar{t}$	182.49	$\pm$	16.56	143.2	$\pm$	23.6
Z +jets	0.27	$\pm$	0.07	27.0	$\pm$	5.5
Single-top	14.77	$\pm$	2.10	15.1	$\pm$	2.0
$t\bar{t} + W/Z$	7.28	$\pm$	1.36	13.3	$\pm$	2.8
$t\bar{t} + h$	12.20	$\pm$	3.92	3.1	$\pm$	1.0
W +jets	5.88	$\pm$	1.87	11.5	$\pm$	2.3
Diboson	1.22	$\pm$	0.51	3.3	$\pm$	0.7

TABLE 4.15: Fit results in the CR and VR defined for the A-type region with an integrated luminosity of 139 fb^{-1} . The results are obtained by performing the background-only fit. The quoted uncertainties on the fitted SM background include both the statistical and systematic uncertainties.

	CRB1 ℓ			VRB0 ℓ		
Observed events	42			93		
Fitted SM bkg events	41.97	$\pm$	6.47	91.66	$\pm$	17.09
$t\bar{t}$	36.29	$\pm$	6.51	67.03	$\pm$	17.12
Z +jets	0.11	$\pm$	0.06	12.09	$\pm$	2.57
Single-top	2.08	$\pm$	0.17	4.25	$\pm$	0.58
$t\bar{t} + W/Z$	1.00	$\pm$	0.18	2.26	$\pm$	0.33
$t\bar{t} + h$	1.41	$\pm$	0.43	0.88	$\pm$	0.27
W +jets	0.85	$\pm$	0.15	3.51	$\pm$	0.67
Diboson	0.23	$\pm$	0.03	1.63	$\pm$	0.48

TABLE 4.16: Fit results in the CR and VR defined for the B-type region with an integrated luminosity of 139 fb^{-1} . The results are obtained by performing the background-only fit. The quoted uncertainties on the fitted SM background include both the statistical and systematic uncertainties.

The CR pre-fit yields and fitted normalisation factors μ_{bkg} for the A-, B- and C-type regions are presented in Figure 4.20. Figure 4.21 presents the observed yields, post-fit background estimates and significance for the A-, B- and C-type VRs. The background-only fit predictions are in good agreement with the data in these regions, and the post-fit expectation is within 1σ of the central value for all regions.

	CRC1 ℓ		CRC2 ℓ		VRC0 ℓ -T		VRC0 ℓ -Z	
Observed events	143		73		118		242	
Fitted SM bkg events	142.99	$\pm$ 11.96	73.02	$\pm$ 8.54	129.44	$\pm$ 19.80	257.49	$\pm$ 40.93
$t\bar{t}$	84.56	$\pm$ 9.96	2.39	$\pm$ 2.15	82.44	$\pm$ 17.72	28.99	$\pm$ 8.68
Z+jets	0.31	$\pm$ 0.11	51.55	$\pm$ 9.37	11.90	$\pm$ 3.04	145.75	$\pm$ 40.27
Single-top	24.02	$\pm$ 2.83	–		14.74	$\pm$ 3.24	19.13	$\pm$ 4.38
$t\bar{t}$ + W/Z	11.18	$\pm$ 1.59	13.07	$\pm$ 2.20	3.27	$\pm$ 0.46	17.51	$\pm$ 2.33
$t\bar{t}$ + h	2.88	$\pm$ 0.89	0.10	$\pm$ 0.04	1.60	$\pm$ 0.49	0.23	$\pm$ 0.08
W+jets	17.26	$\pm$ 2.84	–		13.43	$\pm$ 3.25	32.97	$\pm$ 3.29
Diboson	2.77	$\pm$ 0.35	5.91	$\pm$ 1.74	2.06	$\pm$ 0.52	12.92	$\pm$ 1.54

TABLE 4.17: Fit results in the CRs and VRs defined for the C-type region with an integrated luminosity of 139 fb^{-1} . The results are obtained by performing the background-only fit. The quoted uncertainties on the fitted SM background include both the statistical and systematic uncertainties.

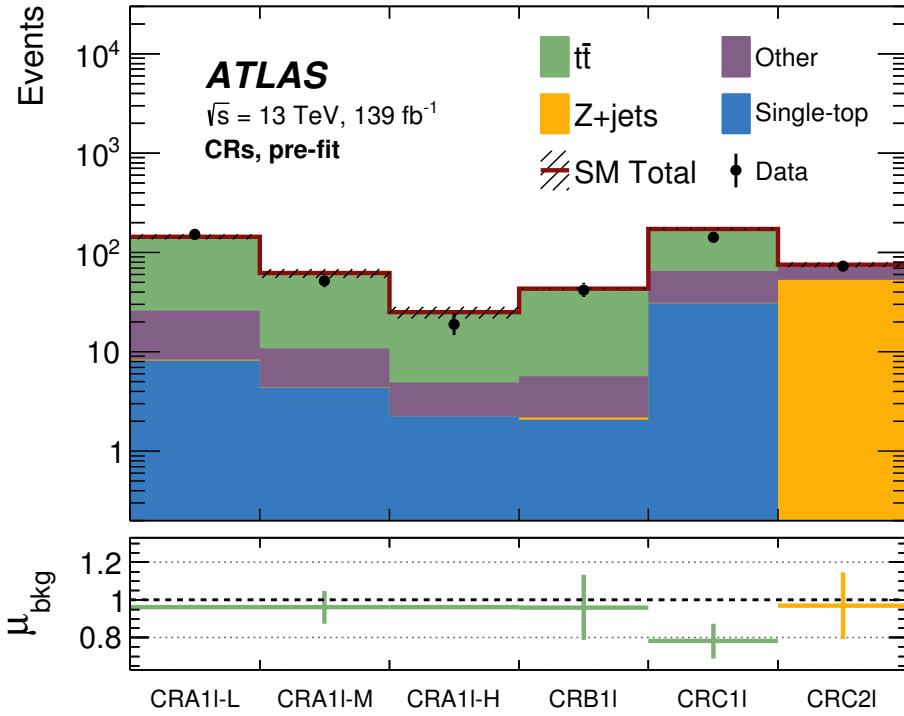


FIGURE 4.20: CR event pre-fit event yields compared with SM MC predictions (top panel) and post-fit μ -factors (bottom panel) for the A-, B- and C-type regions. The uncertainty in the μ -factors and the total expected yield include statistical and systematic uncertainties as introduced in Section 4.8. For the A-type regions, since the fit is performed in the m_{eff} intervals, the normalisation is applied to all bins equally. The minor backgrounds ($t\bar{t}$ + W/Z/h, W+jets and diboson) are grouped and labelled as ‘Other’.

Control Region	CRA1 ℓ	CRB1 ℓ	CRC1 ℓ	CRC2 ℓ
μ -factor	0.948 ± 0.084	0.949 ± 0.170	0.78 ± 0.09	0.97 ± 0.17

TABLE 4.18: Normalisation factors summary for all regions. The uncertainties include statistical and systematic uncertainties.

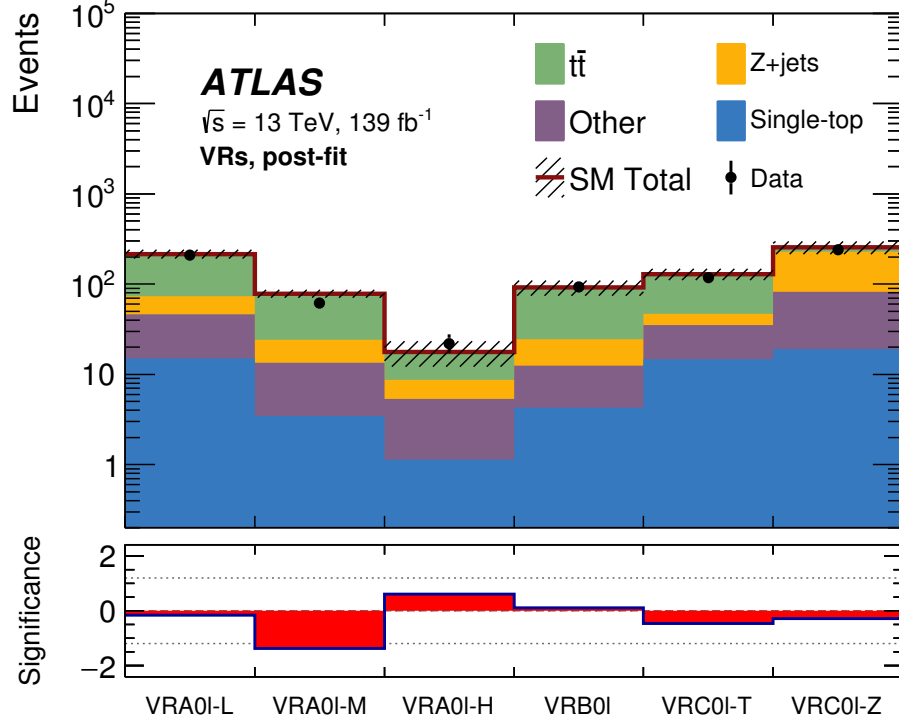


FIGURE 4.21: Results of the background-only fit extrapolated to VRs for the A-, B- and C-type regions. The normalisation of the backgrounds is obtained from the fit to the CRs. The upper panel shows the observed number of events and the predicted background yields. Statistical and systematic uncertainties as introduced in Section 4.8 are included in the uncertainty band. The lower panel shows the significance in each VR. The significance calculation is performed as described in Section 4.6. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’.

The event yields for all SRs throughout the analysis are presented in Table 4.19. The selection criteria used for these signal regions are described in Tables 4.6, 4.7 and 4.8. The SM background expectations resulting from background-only fits are also presented, showing statistical plus systematic uncertainties.

The largest background contribution in the A-type and B-type SRs arises from $t\bar{t}$ production, whilst the contribution from $Z \rightarrow \nu\bar{\nu}$ production in association with b -quarks is largest in the C-type SRs with sub-dominant contributions from the $t\bar{t}$ and single-top processes. Other background processes arise from $t\bar{t} + W/Z$, $t\bar{t} + h$, W +jets and diboson production.

The results are also summarised in Figure 4.22, where the significances for each of the SRs are also presented in the lower panel. No significant deviations from the SM expectation are observed between expected and observed yields in all SRs considered throughout the analysis.

	SRA	SRA-L	SRA-M	SRA-H	SRB
Observed events	17	12	3	2	3
Fitted SM bkg events	17.1 $\pm$ 2.8	8.4 $\pm$ 1.7	5.7 $\pm$ 0.8	3.0 $\pm$ 1.5	3.3 $\pm$ 0.9
$t\bar{t}$	10.1 $\pm$ 2.5	4.7 $\pm$ 1.5	3.7 $\pm$ 0.6	1.7 $\pm$ 1.4	2.3 $\pm$ 0.8
Z +jets	2.6 $\pm$ 0.4	1.3 $\pm$ 0.2	0.9 $\pm$ 0.2	0.4 $\pm$ 0.1	0.3 $\pm$ 0.1
Single-top	1.4 $\pm$ 0.3	0.4 $\pm$ 0.1	0.3 $\pm$ 0.1	0.6 $\pm$ 0.2	0.5 $\pm$ 0.1
$t\bar{t} + W/Z$	1.2 $\pm$ 0.3	0.7 $\pm$ 0.1	0.3 $\pm$ 0.1	0.1 $\pm$ 0.0	0.07 $\pm$ 0.02
$t\bar{t} + h$	1.1 $\pm$ 0.2	0.7 $\pm$ 0.1	0.3 $\pm$ 0.1	0.1 $\pm$ 0.0	0.13 $\pm$ 0.02
W +jets	0.4 $\pm$ 0.1	0.2 $\pm$ 0.1	0.1 $\pm$ 0.0	–	0.02 $\pm$ 0.01
Diboson	0.4 $\pm$ 0.1	0.3 $\pm$ 0.1	–	–	–
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 330, 200)$ GeV	13.7 $\pm$ 0.3	0.7 $\pm$ 0.1	6.3 $\pm$ 0.2	6.6 $\pm$ 0.2	0.3 $\pm$ 0.1
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (700, 680, 550)$ GeV	1.3 $\pm$ 0.6	0.2 $\pm$ 0.1	0.5 $\pm$ 0.4	0.6 $\pm$ 0.4	7.4 $\pm$ 1.2
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1200, 1150, 60)$ GeV	8.7 $\pm$ 0.2	1.4 $\pm$ 0.1	3.4 $\pm$ 0.1	3.8 $\pm$ 0.1	0.6 $\pm$ 0.1

	SRC	SRC22	SRC24	SRC26	SRC28
Observed events	47	28	12	4	3
Fitted SM bkg events	37.9 $\pm$ 6.2	21.2 $\pm$ 4.1	10.6 $\pm$ 2.3	3.7 $\pm$ 0.9	2.4 $\pm$ 0.6
$t\bar{t}$	5.4 $\pm$ 2.6	3.9 $\pm$ 2.3	1.1 $\pm$ 0.6	0.3 $\pm$ 0.3	0.1 $\pm$ 0.1
Z +jets	17.6 $\pm$ 4.7	8.8 $\pm$ 2.5	6.0 $\pm$ 1.8	1.7 $\pm$ 0.7	1.1 $\pm$ 0.4
Single-top	5.0 $\pm$ 1.5	2.7 $\pm$ 1.0	1.2 $\pm$ 0.3	0.7 $\pm$ 0.2	0.4 $\pm$ 0.1
$t\bar{t} + W/Z$	4.3 $\pm$ 0.6	2.5 $\pm$ 0.4	1.1 $\pm$ 0.2	0.5 $\pm$ 0.1	0.2 $\pm$ 0.1
$t\bar{t} + h$	0.2 $\pm$ 0.0	0.2 $\pm$ 0.0	–	0.1 $\pm$ 0.0	0.0 $\pm$ 0.0
W +jets	3.5 $\pm$ 0.8	2.2 $\pm$ 0.5	0.6 $\pm$ 0.2	0.2 $\pm$ 0.1	0.4 $\pm$ 0.1
Diboson	1.8 $\pm$ 0.3	0.9 $\pm$ 0.2	0.6 $\pm$ 0.1	0.2 $\pm$ 0.0	0.1 $\pm$ 0.1
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 330, 200)$ GeV	0.4 $\pm$ 0.1	0.3 $\pm$ 0.1	0.1 $\pm$ 0.0	0.03 $\pm$ 0.02	0.03 $\pm$ 0.01
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (700, 680, 550)$ GeV	1.2 $\pm$ 0.5	0.5 $\pm$ 0.2	0.7 $\pm$ 0.4	–	–
$m(\tilde{b}_1, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1200, 1150, 60)$ GeV	26.7 $\pm$ 0.3	6.3 $\pm$ 0.2	6.4 $\pm$ 0.2	5.8 $\pm$ 0.2	8.3 $\pm$ 0.2

TABLE 4.19: Background-only fit results for the A- and B-type regions (top table) and C-type regions (bottom table) performed using 139 fb⁻¹ of data. The quoted uncertainties on the fitted SM background include both the statistical and systematic uncertainties.

Figures 4.23 to 4.28 present comparisons between the observed data and the post-fit SM predictions for crucial kinematic variable distributions for the A-type, B-type and C-type SRs. Each distribution is produced using the selection for each region before the requirements on the presented quantity are imposed. Arrows indicate the selection on each quantity as part of the full signal region definition. The expected distributions for differing signal scenarios are also depicted, where different bottom-squark, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses are chosen depending on the SR considered.

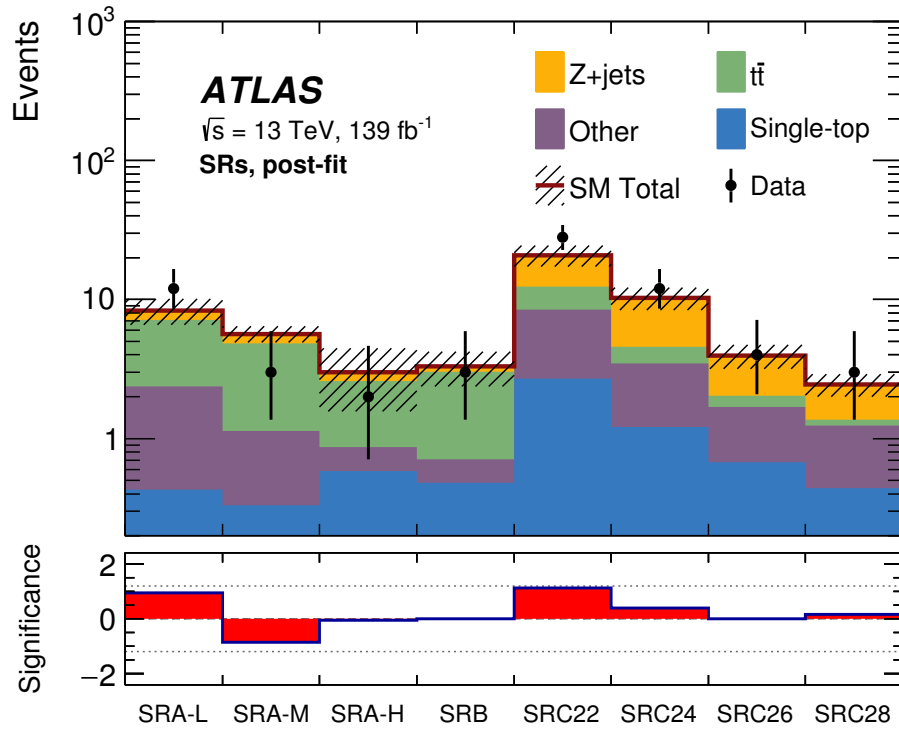


FIGURE 4.22: Results of the background-only fit extrapolated to all SRs. The normalisation of the backgrounds is obtained from the fit to the CRs. The upper panel shows the observed number of events and the predicted background yields. The backgrounds that contribute only a small amount ($t\bar{t}$ + $W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. All uncertainties defined in Section 4.8 are included in the uncertainty band. The lower panel shows the significance in each SR. The significance calculation is performed as described in Section 4.6.

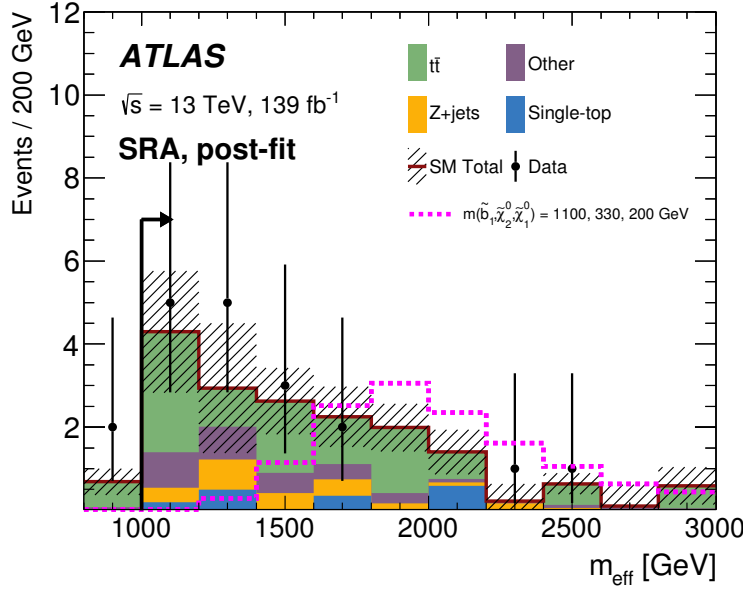


FIGURE 4.23: Post-fit distribution of the m_{eff} for the inclusive A-type SR. All inclusive A-type SR selections are applied except for the selection on m_{eff} , where the full SR criteria incorporates a selection denoted by the arrow. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed. Overflow events that do not fall into the axis range are placed into the right-most bin.

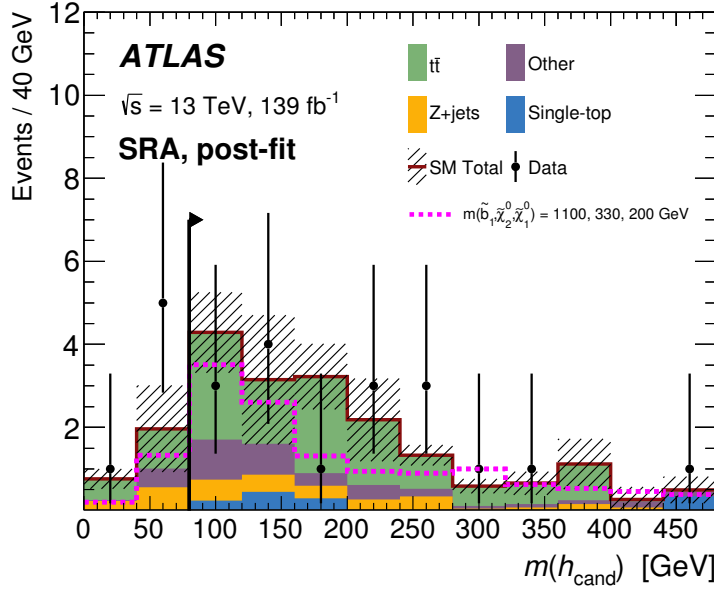


FIGURE 4.24: Post-fit distribution of the invariant mass of the Higgs candidate for inclusive A-type SR. All inclusive A-type SR selections are applied except for the selection on $m(h_{\text{cand}})$, where the full SR criteria incorporates a selection denoted by the arrow. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed. Overflow events that do not fall into the axis range are placed into the right-most bin.

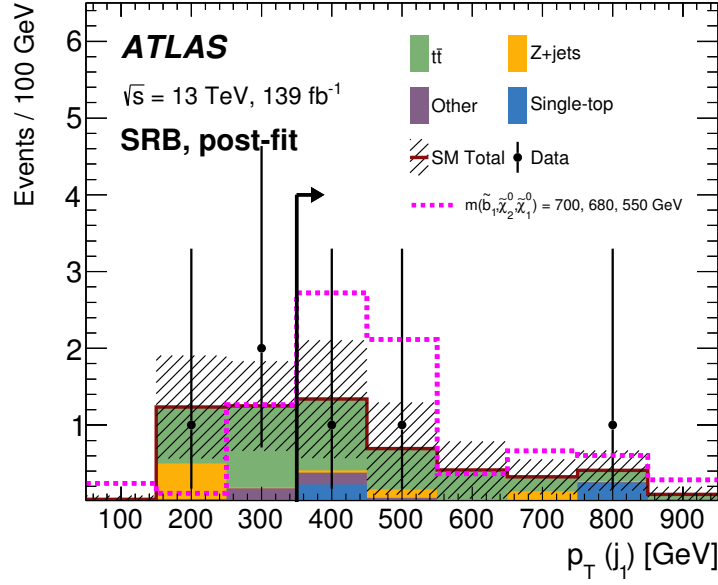


FIGURE 4.25: Post-fit distribution of the p_T of the leading jet for SRB. All SRB selections are applied except for the selection on $p_T(j_1)$, where the full SR criteria incorporates a selection denoted by the arrow. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed. Overflow events that do not fall into the axis range are placed into the right-most bin.

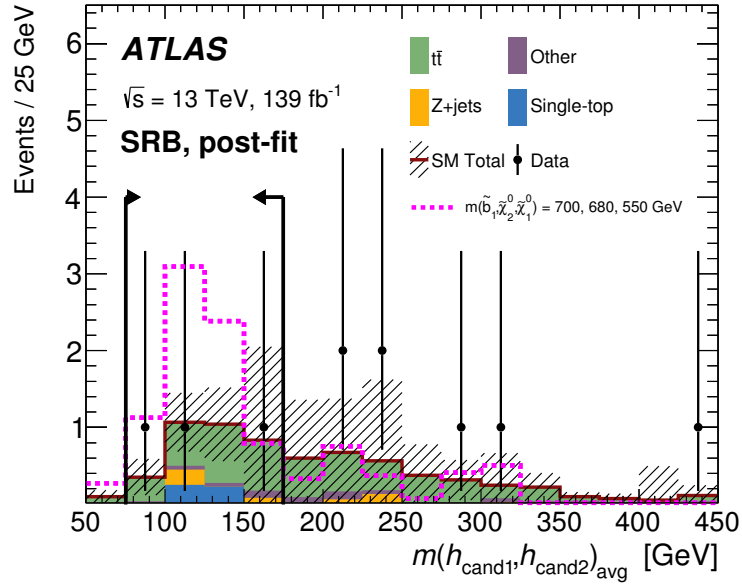


FIGURE 4.26: Post-fit distribution of the average invariant mass of the Higgs candidates for SRB. All SRB selections are applied except for the selection on $m(h_{\text{cand1}}, h_{\text{cand2}})_{\text{avg}}$, where the full SR criteria incorporates a selection denoted by the arrow. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed. Overflow events that do not fall into the axis range are placed into the right-most bin.

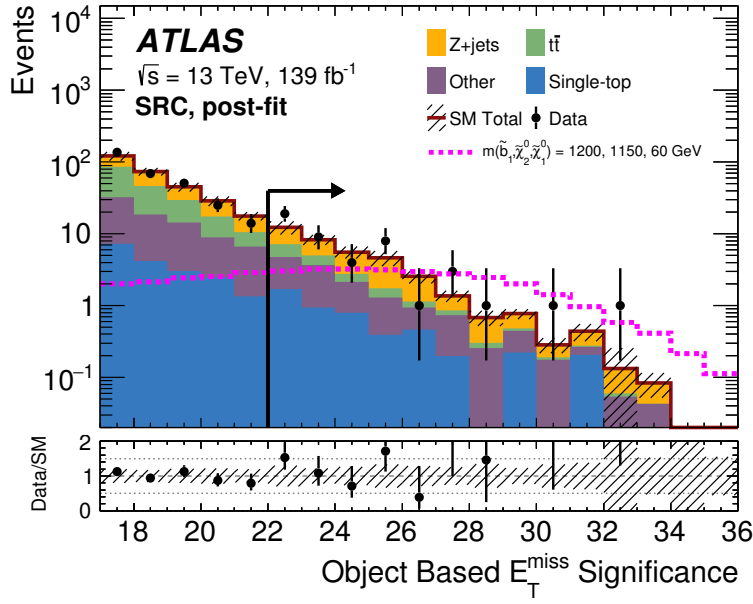


FIGURE 4.27: Post-fit distribution of the object based E_T^{miss} -significance ($\mathcal{S}$) for SRC. All SRC selections are applied except for the selection on $\mathcal{S}$, where the full SR criteria incorporates a selection denoted by the arrow. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed. Overflow events that do not fall into the axis range are placed into the right-most bin.

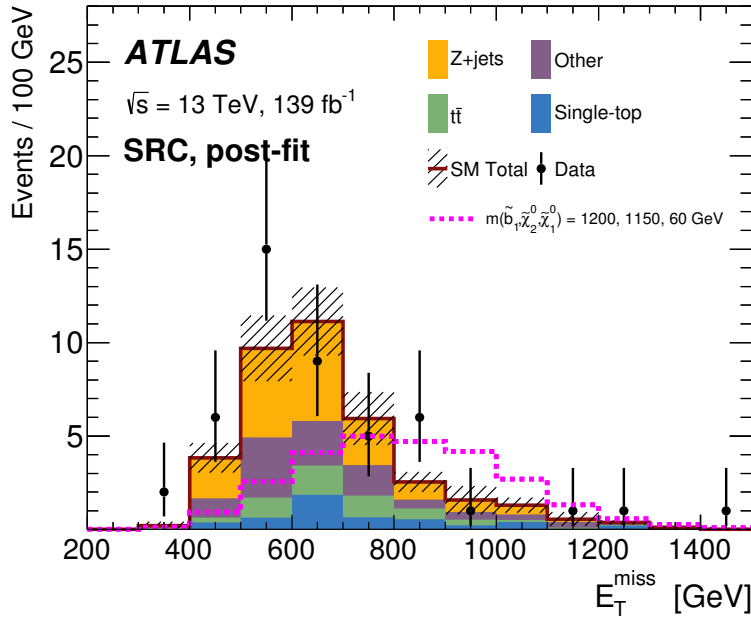


FIGURE 4.28: Post-fit distribution of the E_T^{miss} for SRC. All SRC selections are applied. All uncertainties as defined in Section 4.8 are included in the uncertainty band. The minor backgrounds ($t\bar{t} + W/Z/h$, W +jets and diboson) are grouped and labelled as ‘Other’. For illustration, the expected contribution from a given signal mass scenario is superimposed.

Overflow events that do not fall into the axis range are placed into the right-most bin.

4.10 Interpretation

Whilst there are minimal discrepancies in the observed and expected number of events in the SRs, they are not statistically significant and are within the associated uncertainties. In the absence of a significant deviation from the number of expected SM events, limits on both generic models of new physics and on the signal models in question are derived.

Limits on the cross-section of a generic BSM process are placed using the model-independent fit procedure, where the CL_s technique [195] is used to place 95% CL upper limits on the event yields from potential BSM physics in each of the SRs. The profile likelihood ratio test statistic is used to exclude the signal-plus-background hypothesis for individual signal models. By normalising these results to the full integrated luminosity of the data sample, they can be interpreted as corresponding upper limits on the visible cross-section, σ_{vis} , defined as the product of the BSM production cross-section, the acceptance and the selection efficiency of a BSM signal. The inclusive A- and C-type SR selections are used while calculating the model-independent upper limits in these regions.

Table 4.20 presents the observed (S_{obs}^{95}) and expected (S_{exp}^{95}) 95% CL upper limits on the number of BSM events and on σ_{vis} for all SRs. The p_0 -values represent the probability of the SM background to fluctuate to at least the observed number of events and are capped at $p_0 = 0.5$; the associated significance is provided in parentheses.

Signal channel	$\sigma_{\text{vis}}[\text{fb}]$	S_{obs}^{95}	S_{exp}^{95}	CL_B	p_0 (Z)
SRA	0.06	9.0	$10.1^{+4.7}_{-3.1}$	0.38	0.50 (0.00)
SRB	0.04	4.9	$5.1^{+2.8}_{-1.7}$	0.45	0.50 (0.00)
SRC	0.19	26.0	$20.8^{+7.0}_{-5.5}$	0.80	0.17 (0.97)

TABLE 4.20: From left to right, observed 95% CL upper limits on the visible cross-sections σ_{vis} , the observed (S_{obs}^{95}) and expected (S_{exp}^{95}) 95% CL upper limits on the number of signal events with $\pm 1 \sigma$ excursions of the expectation, the CL of the background-only hypothesis, CL_B , the discovery p -value (p_0), truncated at 0.5, and the associated significance (in parentheses).

Model-dependent exclusion limits are obtained for the two signal scenarios introduced in Section 4.1. The lightest bottom-squark decays exclusively via $\tilde{b}_1 \rightarrow b\tilde{\chi}_2^0$ with subsequent decay $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$. The expected limits from the SRs are compared for each set of scenarios and the observed limits are obtained by choosing the SR with the best expected sensitivity for each signal model. The fit procedure takes into account correlations in the yield predictions between CRs and SRs due to common background normalisation parameters and systematic uncertainties. The experimental systematic uncertainties in the signal are taken into account for the calculation and are assumed to be fully correlated with those in the SM background.

Figures 4.29 and 4.30 present the observed and expected exclusion contours at 95% CL in the $\tilde{b}_1$ – $\tilde{\chi}_2^0$ mass plane for the inclusive A-type SR and inclusive C-type SR for the $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ signal scenario. Figures 4.31 and 4.32 present the observed and expected exclusion contours at 95% CL in the $\tilde{b}_1$ – $\tilde{\chi}_2^0$ mass plane for the inclusive A-type SR and SRB for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}$ signal scenario. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model. The expected CL values are also presented at each signal scenario point for both signal scenarios.

Exclusion limits presented for the $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ signal scenario include a grey shaded area, which depicts the previously excluded region from ATLAS Run 1, taken from [63].

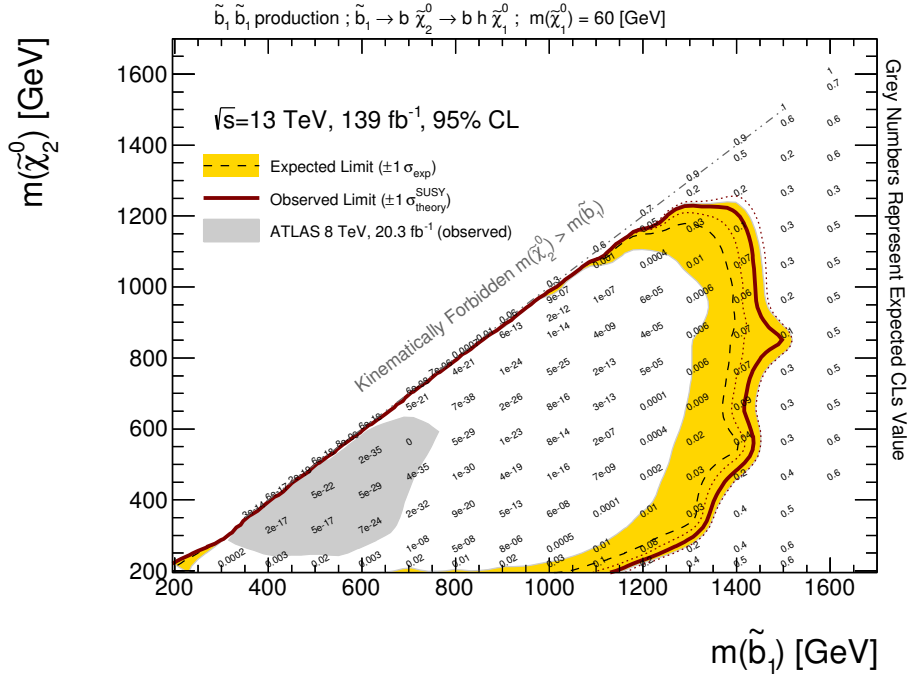


FIGURE 4.29: Expected and observed exclusion limits at 95% CL for the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space, showing the exclusion for inclusive A-type SR. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model.

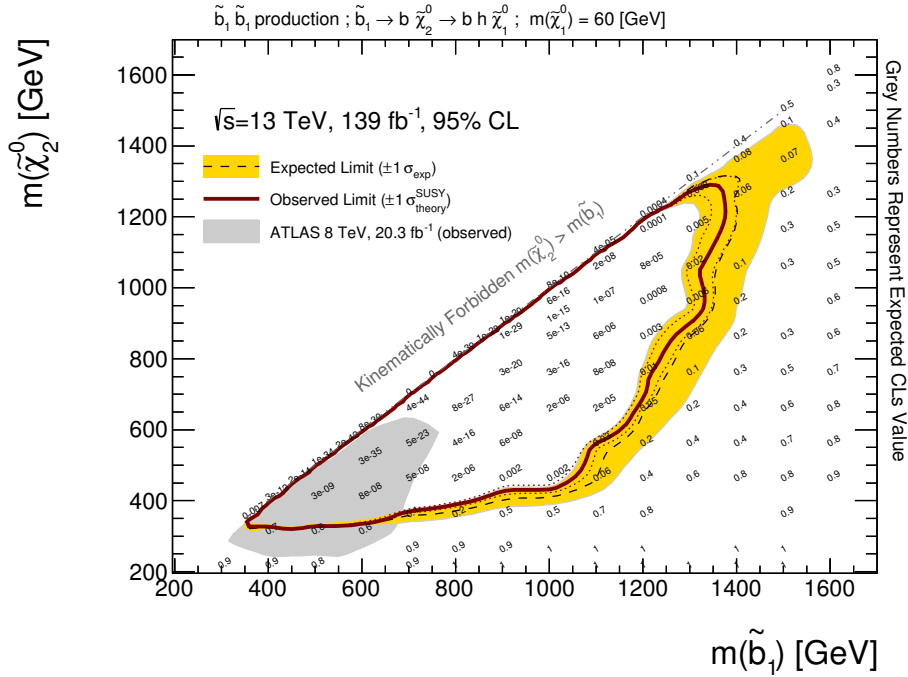


FIGURE 4.30: Expected and observed exclusion limits at 95% CL for the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space, showing the exclusion for inclusive C-type SR. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model.

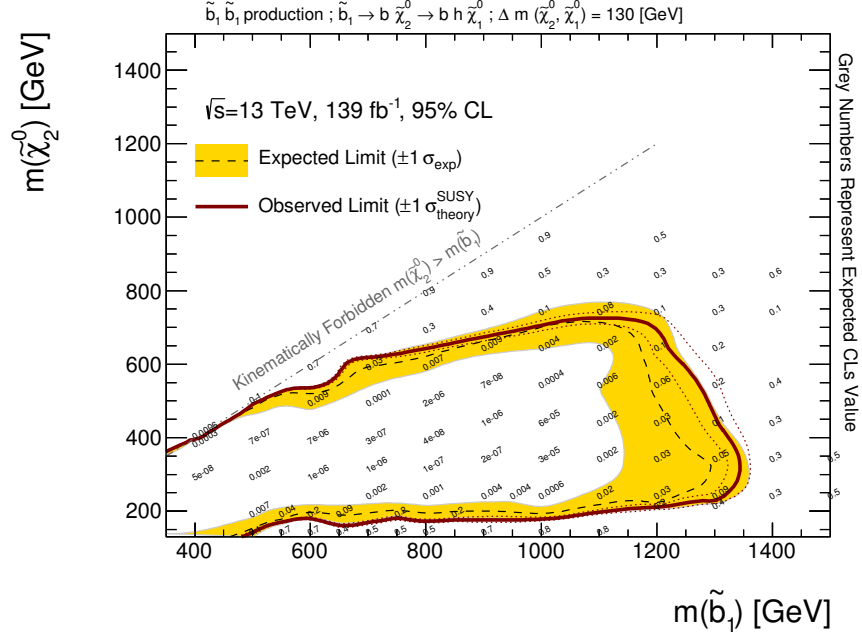


FIGURE 4.31: Expected and observed exclusion limits at 95% CL for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space, showing the exclusion for inclusive A-type SR. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model.

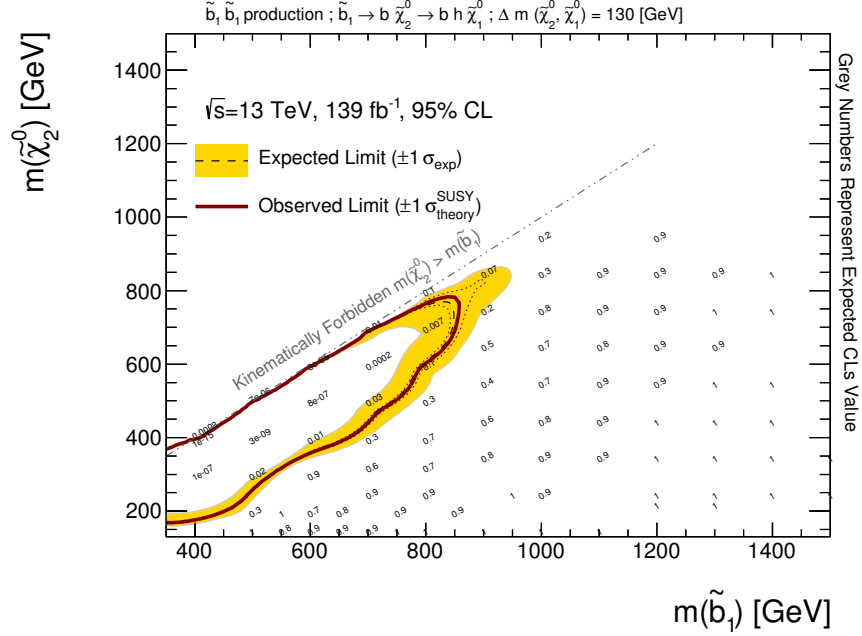


FIGURE 4.32: Expected and observed exclusion limits at 95% CL for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space, showing the exclusion for SRB. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model.

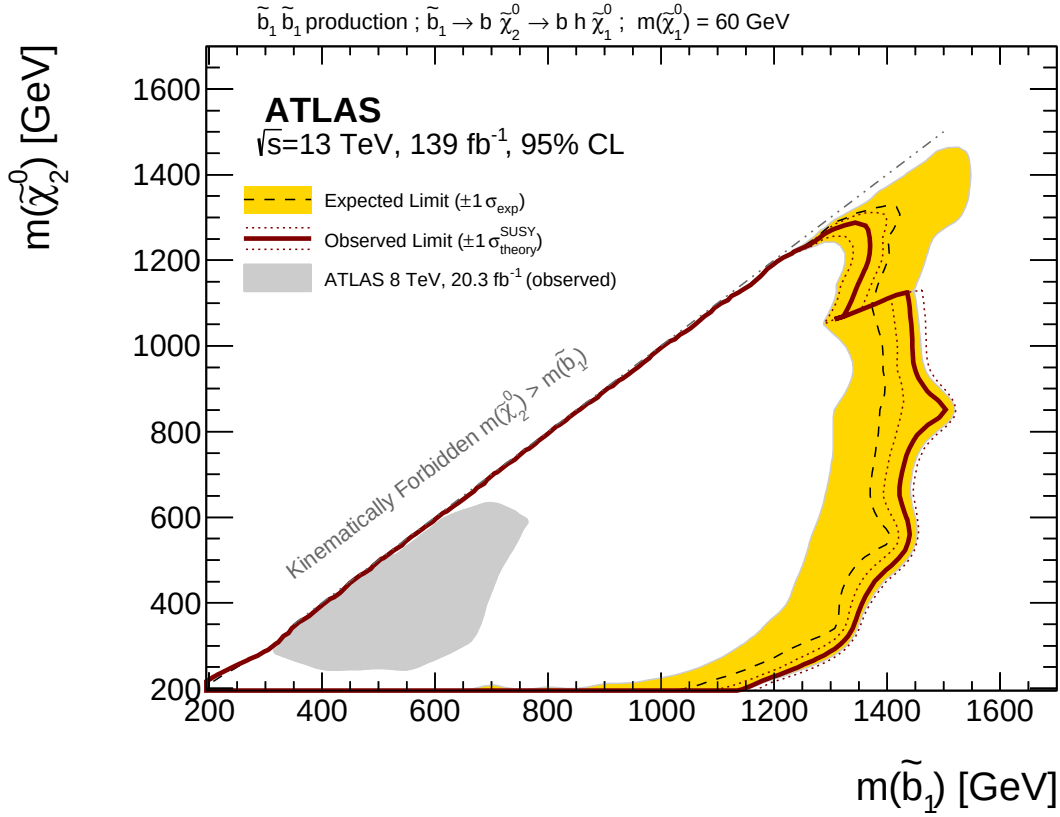


FIGURE 4.33: Exclusion contour at the 95% CL in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space for the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario, using the SR with the best-expected sensitivity. The theory uncertainty band contains the systematic uncertainties on the signal model under consideration and the uncertainty in the signal cross-section.

Figures 4.33 and 4.34 present the observed and expected best combined exclusion contours at 95% CL in the $\tilde{b}_1$ - $\tilde{\chi}_2^0$ mass planes for the two signal scenarios considered. The exclusion limit for the $m(\tilde{\chi}_1^0) = 60$ GeV scenario combines the exclusion limits from the A-type SRs and the C-type SRs, where the SR that performs best at each signal scenario is used to derive the limit presented. While the exclusion limit for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenario combines the exclusion limits from the A-type SRs and the B-type SR.

Figures 4.35 and 4.36 show the best combined exclusion contours at 95% CL in the $\tilde{b}_1$ - $\tilde{\chi}_2^0$ mass planes for the two signal scenarios considered, whilst additionally labelling the SR that performed best at each individual signal model. For the scenarios with $m(\tilde{\chi}_1^0) = 60$ GeV, the sensitivity to models with the largest mass difference between the $\tilde{b}_1$ and the $\tilde{\chi}_2^0$ is achieved with the combination of the A-type SRs. Sensitivity to scenarios with small mass differences is obtained with the dedicated C-type SRs. For scenarios with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, the sensitivity of the A-type SRs is complemented by the B-type SR in the case of small mass difference between the $\tilde{b}_1$ and the $\tilde{\chi}_2^0$. Therefore, as intended, the bulk of the signal models are covered by the A-type SRs, while the compressed regions of both of the scenarios are best excluded by the complementary SRs designed for this purpose.

Additional exclusion limits presenting the expected CL values and the upper limit on the cross-section for the best combined exclusion contours for the $m(\tilde{\chi}_1^0) = 60$ GeV and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenarios can be found in Appendix A.

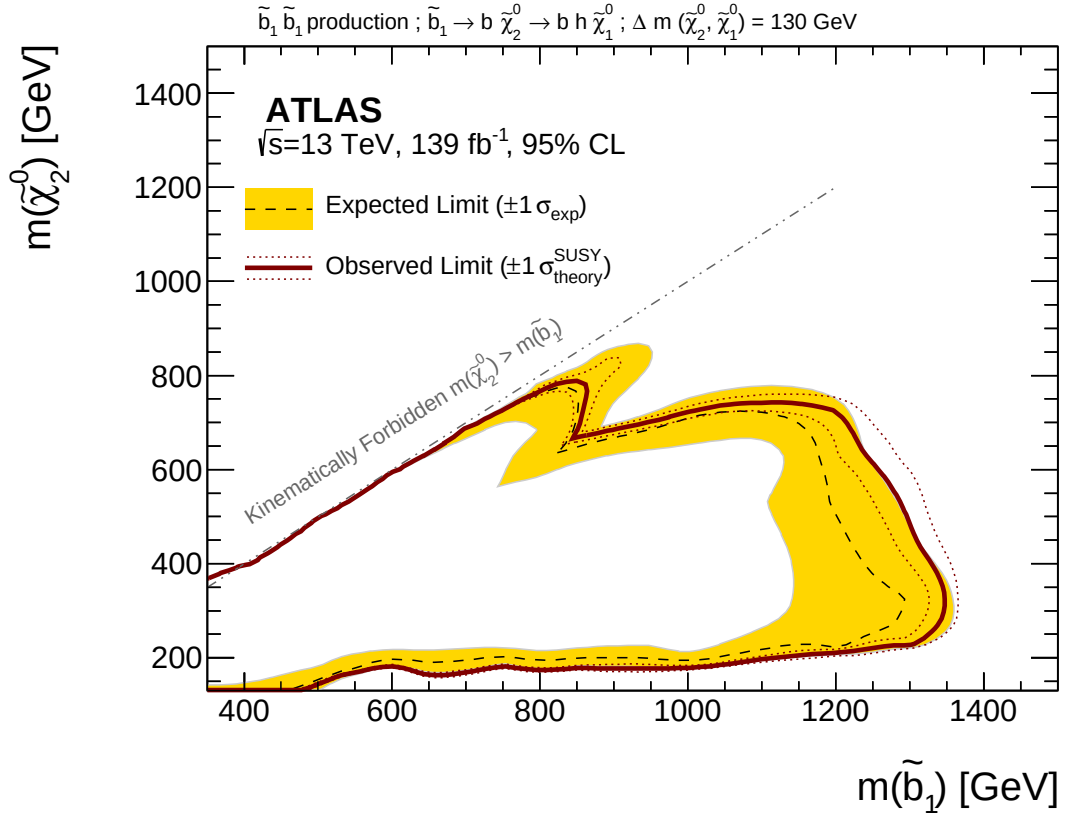


FIGURE 4.34: Exclusion contour at the 95% CL in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario, using the SR with the best-expected sensitivity. The theory uncertainty band contains the systematic uncertainties on the signal model under consideration and the uncertainty in the signal cross-section.

The observed limit is seen to either exclude further or not as powerfully as the expected exclusion limits. This difference in observed and expected is a consequence of the event yields in each SR. As can be seen in Figure 4.22, there is a general deficit in the observed number of events with respect to the expected number of events for the A-type SRs. This deficit increases the exclusion limit since it is statistically less likely that there is an excess in events coming from BSM physics. Whereas for the C-type SRs, there is generally a slight excess, which in turn decreases the exclusion limit, since it is less probable that this excess is from only SM events, and hence the associated CL decreases.

Bottom-squark masses up to 1.5 TeV are excluded for models with fixed $m(\tilde{\chi}_1^0) = 60$ GeV and $\tilde{\chi}_2^0$ masses $\in [0.5, 1.1]$ TeV. In the case of the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario, bottom-squark masses up to 1.3 TeV are excluded for $\tilde{\chi}_2^0$ masses up to 750 GeV. The loss in sensitivity for models where $\tilde{\chi}_2^0$ masses are below 190 GeV are due to the stringent requirements on E_T^{miss} .

The results constitute a large improvement upon previous Run 1 searches and significantly strengthen the constraints on bottom-squark masses. Figure 4.37 depicts the combined best exclusion on the bottom-squark mass as a function of the mass of the neutralino from the ATLAS experiment as of July 2019, where the analysis presented can be seen as the green exclusion limit line. The results of the analysis are complementary to other searches where bottom-squarks are assumed to decay directly to a bottom-quark and a neutralino or to a top-quark and a chargino, depicted by the blue line in Figure 4.37 [71].

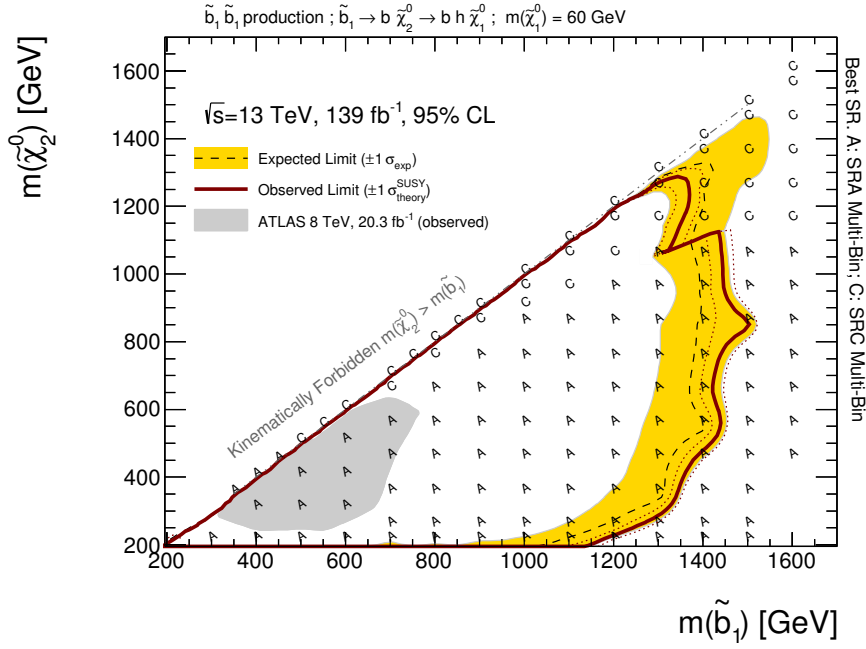


FIGURE 4.35: Exclusion contour at the 95% CL in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space for the $m(\tilde{\chi}_1^0) = 60$ GeV signal scenario, using the SR with the best-expected sensitivity. The theory uncertainty band contains the systematic uncertainties on the signal model under consideration and the uncertainty in the signal cross-section. The letters represent the SR that performs best at each individual signal model.

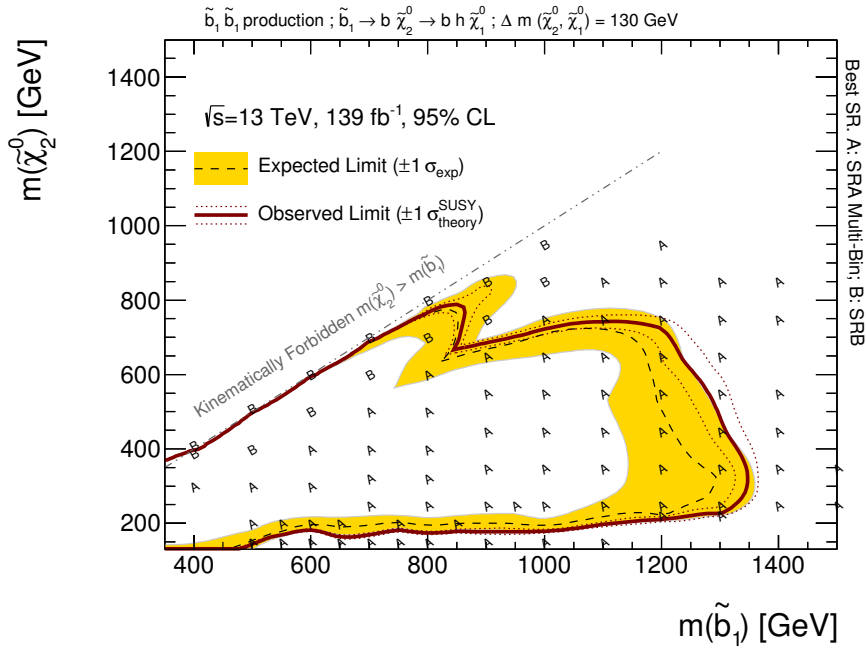


FIGURE 4.36: Exclusion contour at the 95% CL in the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenario, using the SR with the best-expected sensitivity. The theory uncertainty band contains the systematic uncertainties on the signal model under consideration and the uncertainty in the signal cross-section. The letters represent the SR that performs best at each individual signal model.

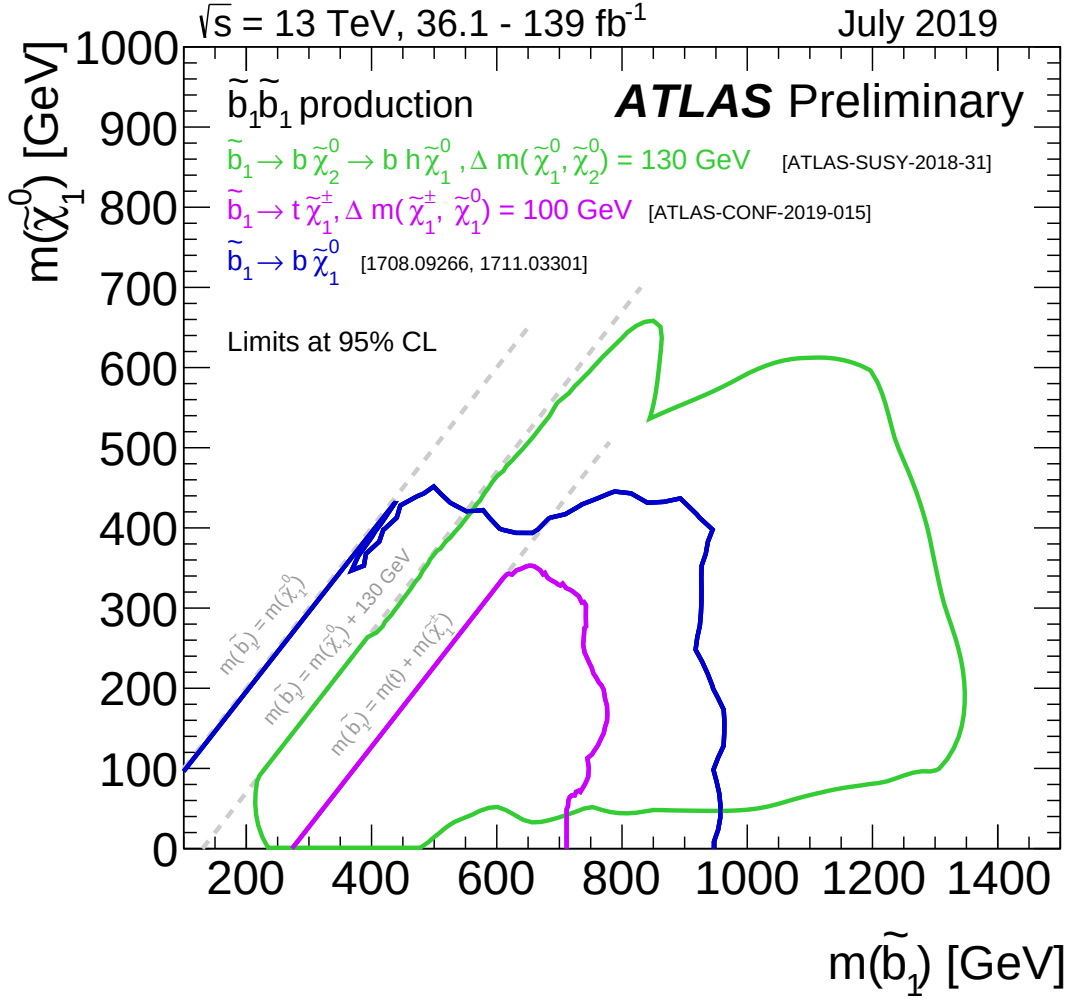


FIGURE 4.37: Exclusion limits at 95% CL in the $m(\tilde{b}_1, \tilde{\chi}_1^0)$ phase space for direct bottom-squark production. The lightest neutralino ($\tilde{\chi}_1^0$) is assumed to be the lightest supersymmetric particle (LSP). Several different decay scenarios are shown, along with different parameterisations of the intermediate particles in the models. Taken from [201].

Presented in this Chapter are the results of a search for pair production of bottom-squarks. The analysis uses 139 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ collected by the ATLAS experiment at the LHC between 2015 and 2018. R -parity-conserving supersymmetry scenarios are considered, where bottom-squarks decay into a b -quark and the second-lightest neutralino, $\tilde{b}_1 \rightarrow b + \tilde{\chi}_2^0$, with $\tilde{\chi}_2^0$ subsequently decaying into a SM-like Higgs boson and the lightest neutralino. The search targets final states containing large missing transverse momentum and three or more b -jets. Two justified signal scenarios are considered, where the mass difference between the second-lightest neutralino and the lightest neutralino is fixed at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}$; and a fixed mass neutralino at $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$.

Dedicated SRs are designed to investigate particular regions of the $m(\tilde{b}_1, \tilde{\chi}_2^0)$ phase space for both of the signal scenarios in consideration, where kinematic features are exploited in order to reject SM background events. The A-type SRs cover the majority of the signal models, and rely on a Higgs identification method by reconstructing the b -quark pair from the subsequent decay. Complementary SRs are used to target the low mass splitting region, referred to as the compressed signal scenarios, where the kinematics of the targeted events are substantially altered, and hence optimised SRs for both of the signal scenarios separately are utilised.

No significant excess of events above the expected SM background is found in any of the SRs across the analysis, where exclusion limits at the 95% CL are placed on the visible cross-section and on the mass of the bottom-squark for various assumptions about the mass hierarchy of the $\tilde{b}_1$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. Bottom-squark masses up to 1.5 TeV are excluded for $\tilde{\chi}_2^0$ masses up to 1100 GeV in models with fixed $m(\tilde{\chi}_1^0) = 60$ GeV. Whilst bottom-squark masses up to 1.3 TeV are excluded for $\tilde{\chi}_2^0$ masses up to 750 GeV in models with fixed $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV.

As the first search for such scenarios carried out by ATLAS in Run 2, these results represent a significant improvement upon the previous Run 1 result, considerably increasing the constraints on bottom-squark production.

Chapter 5

High-Luminosity LHC and ATLAS Upgrade

5.1 The LHC Upgrade Schedule

The LHC run schedule has operated typically with periods of data-taking separated by technical shutdowns, during which maintenance and upgrades are performed on the accelerator machines and the detectors. A summary of the LHC operation timeline is shown in Figure 5.1. With the end of Run 2, the LHC delivered 156 fb^{-1} of proton-proton collisions, achieving an instantaneous luminosity of $\mathcal{L} = 2.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an average number of interactions per bunch crossing of $\langle \mu \rangle = 33.7$. The end of Run 2 marks the beginning of another long-shutdown period, referred to as LS2, which is planned to last for two years, during which the injection chain will be upgraded in order to allow for instantaneous luminosities of $\mathcal{L} = 5.0 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The centre-of-mass energy will be increased to the nominal 14 TeV design energy, where, combined with the already recorded data, the ATLAS detector expects to record up to 300 fb^{-1} of data.

After Run 3, it is scheduled that the long-shutdown III (LS3) will begin, whereby the LHC will then enter the next phase of its operation: the High-Luminosity LHC (HL-LHC), which is planned for 2026. This phase will see the instantaneous luminosity significantly increased, up to $\mathcal{L} = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, Followed by a decade of data-taking that will amount to up to 4000 fb^{-1} since the beginning of LHC operation. The HL-LHC will operate at the nominal design centre-of-mass energy of the current LHC, with the intent of significantly increasing the luminosity in order to study very rare processes.

This increase in luminosity has substantial implications for the experiments at LHC. The harsher radiation environment will necessitate significant upgrades to the ATLAS detector, particularly to the sub-systems closest to the interaction point. The current ID will be entirely replaced by an all-silicon based detector called the Inner Tracker (ITk) [202, 203], which will be designed to perform at a high detection efficiency with a fast timing response after high radiation doses with large particle multiplicity and a predicted number of interactions per bunch crossing of $\langle \mu \rangle = 200$. The upgrades will encompass the silicon pixel sensors, the readout electronics, and detector services. The current electromagnetic and hadronic calorimeters are expected to perform effectively even during the HL-LHC phase. The muon spectrometer will see upgrades to improve the performance of the muon trigger chambers. The readout capability will be increased from the current 100 kHz up to 1 MHz, with the data written to storage increasing from 1 kHz up

to 10 kHz. The trigger architecture will be designed to have access to the tracking information from ITk and to the calorimeter hit data.

The current ATLAS pixel detector was designed to operate at a maximum integrated fluence of $\sim 10^{15}$ 1 MeV $n_{\text{eq}}/\text{cm}^2$ ¹, corresponding to an integrated luminosity of 400 fb^{-1} [204, 206]. The IBL was designed to operate at luminosities up to 850 fb^{-1} , where the expected fluence at this radius in ITk is $1.31 \cdot 10^{16} n_{\text{eq}}/\text{cm}^2$ [203], and hence the radiation tolerance of the current detector is inadequate for the foreseen HL-LHC phase. The inner layers will also need to contribute to the material budget $X_0 < 1.5\%$ at the innermost layer, and to $X_0 < 2.0\%$ at the outermost. The SCT is also not sufficiently radiation hard, where the design limit is $2 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$ compared to the expected $10^{15} n_{\text{eq}}/\text{cm}^2$ [202, 205].

The highly successful concept of hybrid pixel detectors that were developed for and implemented in the current ATLAS pixel detector are an obvious candidate to instrument the ITk. High resistivity, planar and 3D, silicon detectors have proved to be radiation tolerant, while performing effectively within the ATLAS pixel layers and IBL. The decision on technology is largely driven by the radiation tolerance requirements and the need for finer pixel granularity, increased bandwidth and reduced material. An exciting candidate for the outermost pixel layers of the ITk is based on the high-voltage CMOS (HV-CMOS) process [207–209], and could offer reduced power consumption and material, whilst the commercial availability of this technology would drastically decrease the cost of production.

This chapter presents a study assessing the radiation tolerance and performance of HV-CMOS pixel sensors as a viable option for the ITk upgrade to the ATLAS detector as part of the planned HL-LHC phase.

¹The unit of 1 MeV $n_{\text{eq}}/\text{cm}^2$, read as a 1 MeV neutron equivalence per square centimetre, is used as the benchmark whilst comparing fluences; commonly abbreviated to $n_{\text{eq}}/\text{cm}^2$.

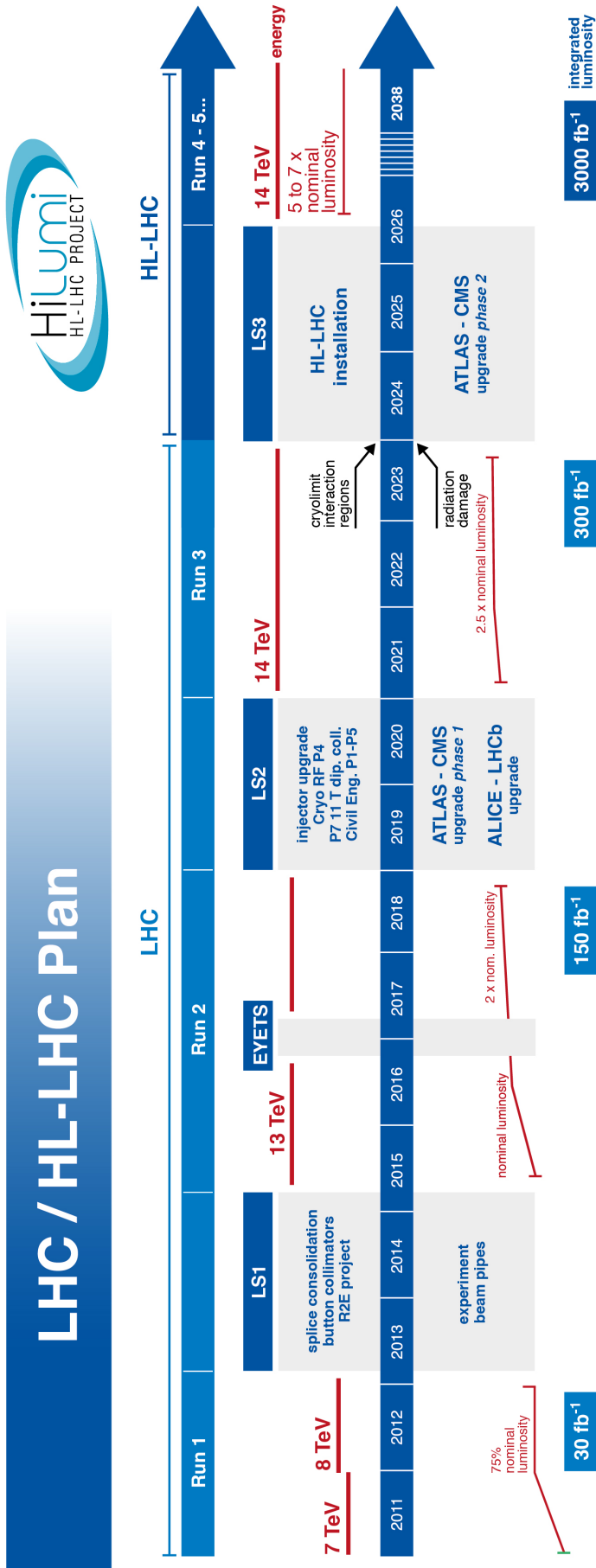


FIGURE 5.1: LHC timeline spanning the LHC to the HL-LHC era, indicating the data-taking periods along with the shutdown periods. Taken from [248].

5.2 ATLAS Upgrade: Inner Tracker

The Inner Tracker (ITk) is an all-silicon detector that is intended to provide good performance throughout the HL-LHC phase. The current design mimics the present ATLAS ID, comprising of pixel detector layers surrounded by strip detectors. The pixel detector is composed of five barrel layers and four end-cap ring layers, which will provide hermetic tracking up to $|\eta| = 4$ [203]. The strip detector is composed of four barrel layers and six discs situated adjacent to the pixel end-caps [202]. The proposed arrangement is presented schematically in Figure 5.2.

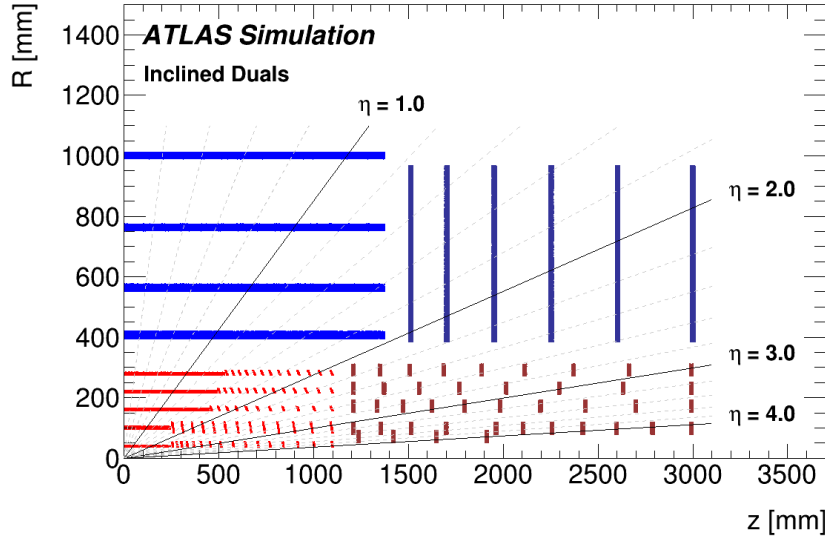


FIGURE 5.2: A schematic layout of the current design of the ITk for the HL-LHC phase. One quarter of the detector is shown, where only the active detector components are depicted. The active components of the barrel and end-cap strip detector are shown in blue, while for the pixel detector they are shown in red for the barrel layers and in dark red for the end-cap rings. The horizontal axis is parallel to the beam line, where the origin represents the interaction point. The vertical axis is the radius measured from the interaction point [249].

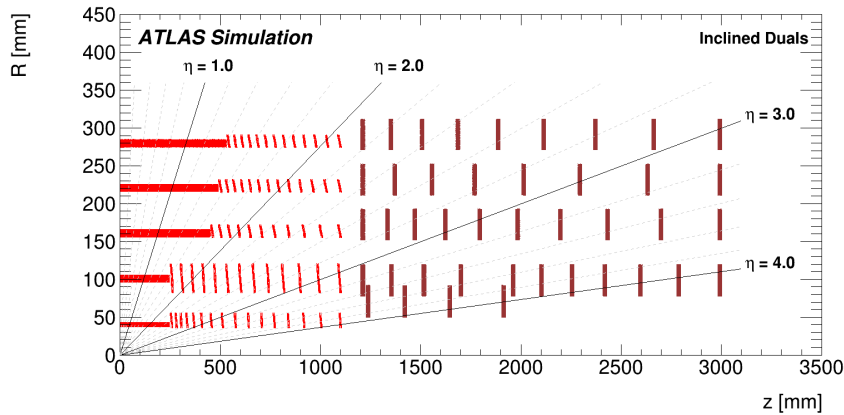


FIGURE 5.3: Schematic of the ITk pixel detector. One quarter of the detector is shown, where only the active detector components are depicted. The pixel detector layers are shown in red for the barrel layers and in dark red for the end-cap rings. The horizontal axis is parallel to the beam line, where the origin represents the interaction point. The vertical axis is the radius measured from the interaction point [249].

The current pixel detector layout incorporates two novel design ideas that intend to ensure a more constant number of hits in both the pixel and strip detectors as a function of pseudorapidity:

an inclined barrel stave design and the end-cap ring system. The inclined barrel stave design introduces an angular offset in the outer section of the barrel layers, as is depicted in Figure 5.3. The angular offset minimises the loss of performance due to inactive material situated in the transition region between the barrel and end-cap sections of the pixel detector. The angular offset also reduces the amount of silicon required since each of the inclines modules has an extended angular coverage with respect to a flat design [203]. The end-cap ring system is designed to extend the active instrumented surface further along the z -axis, while also allowing for efficient routing of the essential services along each ring layer separately. The introduction of both of these ideas, in particular the inclined barrel design, ensures that an average number of hits exceeds 9 in all of the instrumented $|\eta|$ region [203].

Table 5.1 summarises the required detection surface area for the different sections of the ITk pixel detector. In total, the active detection surface equates to 12.74 m^2 .

Detector Section	Surface Area [m^2]
Inner barrel flat	0.52
Inner barrel inclined	1.00
Inner barrel total	1.51
Outer barrel flat	4.49
Outer barrel inclined	2.30
Outer barrel total	6.79
Barrel total	8.30
End-cap inner rings	0.94
End-cap outer rings	3.50
End-cap rings total	4.44
Total	12.74

TABLE 5.1: Summary of the required active detection surface area for each component of the ITk pixel detector. Taken from [203].

The staves of the barrel section and the rings of the end-caps will be instrumented with hybrid modules similar to those populating the current ATLAS pixel detector. These modules will consist of a passive, high-resistivity silicon pixel sensor, which will be bump-bonded to a front-end (FE) readout chip fabricated in CMOS technology. Different sensor technologies will be utilised depending on the expected fluence at the given layer radius. The innermost layer will be populated using 3D silicon detectors. This sensor technology features electrodes that extend into the sensor bulk perpendicular to the surface, an intrinsic feature that ensures high radiation tolerance since the distance between the electrodes is unaffected by the thickness of the sensor. The electrode separation can be substantially smaller than the thickness of a conventional planar sensor, where the electrodes are implanted in the surface side of the sensor and extends hundreds of micrometers in depth. This reduced distance results in less charge trapping from radiation-induced defects in the silicon bulk and also allows for lower operating bias voltages [210]. The technology expected to populate the remaining layers is the well-established planar sensor.

Three different module sizes will be used throughout the system: single readout chip modules ($20 \times 20 \text{ mm}^2$) in the inclined section of the barrel layer 0; dual readout chip modules ($20 \times 40 \text{ mm}^2$)

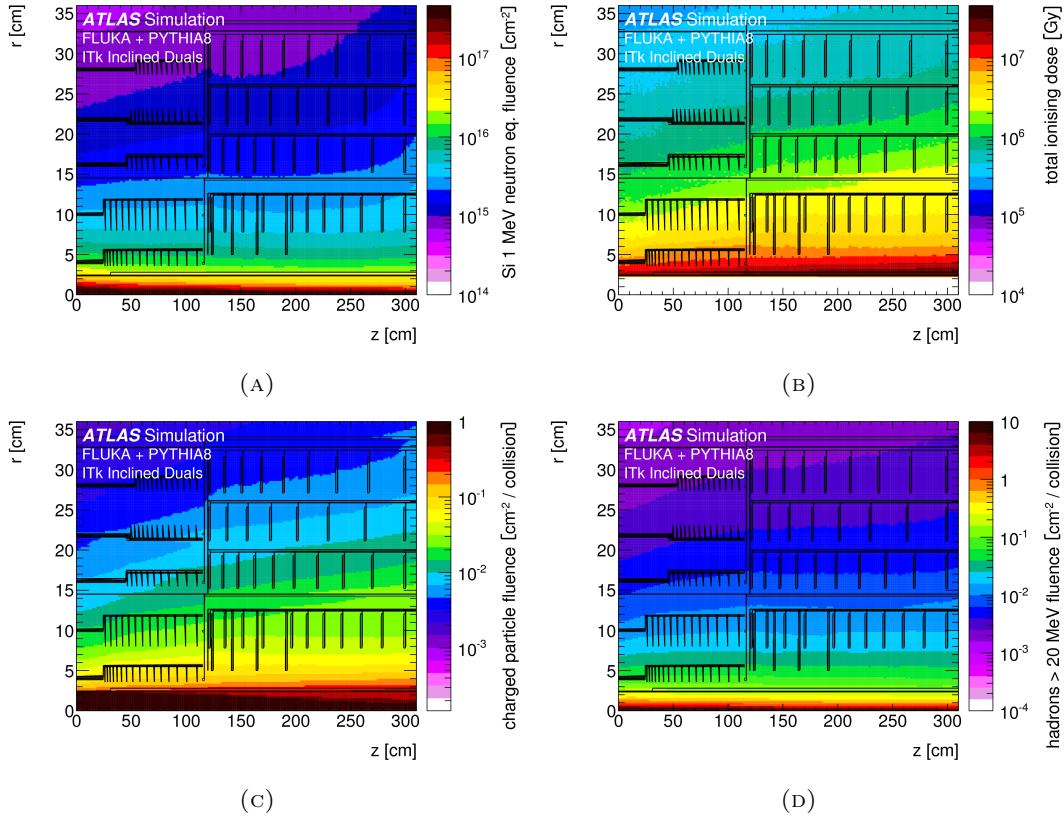


FIGURE 5.4: The fluence and dose distributions for the ITk pixel detector. (A) 1 MeV neutron equivalent fluence. (B) Total ionising dose. (C) Charged particle fluence. (D) Hadron fluence for energies greater than 20 MeV. The distributions presented in (A) and (B) are normalised to 4000 fb^{-1} [249].

in the flat section of the barrel layer 0; quad readout chip modules ($40 \times 40 \text{ mm}^2$) will populate the remaining layers, aside from barrel layers 2 to 4, where the technology to be used is as of yet undecided. In total, more than 10k modules are required to instrument the detector, of which there will be ~ 500 single modules, 3.2k dual modules and $\sim 6.5\text{k}$ quad modules.

Given the significant increase in luminosity and the number of interactions per bunch crossing, the expected radiation levels in the ATLAS ITk is expected to increase by approximately an order of magnitude with respect to the current ID. Simulations of the radiation have been performed for ITk using the PYTHIA [186] event generator and the FLUKA [211] particle transport code. The expected fluences and received doses throughout the volume of the pixel detector are presented in Figure 5.4. It is expected that the fluences in the innermost layers of the barrel section are mostly from particles produced directly at the interaction point, whereas the expected fluences in the outer barrel layers and the end-cap layers are increasingly dominated by particles produced during secondary interactions in the calorimeter, pixel service material and the beam line itself.

It is also foreseen that the outer pixel barrel and end-cap detector will be operated to collect a total integrated luminosity of up to 4000 fb^{-1} , while the inner barrel and end-caps will be replaced after 2000 fb^{-1} . A summary of the maximum 1 MeV neutron equivalent fluences for the different sections of the ITk pixel detector are presented in Table 5.2.

Luminosity	Layer	Location	R [cm]	z [cm]	Fluence [$10^{14} n_{\text{eq}}/\text{cm}^2$]
2000 fb^{-1}	0	Flat barrel	3.9	0.0	131
			4.0	24.3	-
		Inclined barrel	3.7	25.9	123
			3.7	110.0	-
		End-cap	5.1	123.8	68
2000 fb^{-1}	1	Flat barrel	9.9	24.3	27
		Inclined barrel	8.1	110.0	35
		End-cap	7.9	299.2	38
4000 fb^{-1}	2-4	Flat barrel	16.0	44.6	28
		Inclined barrel	15.6	110.0	30
		End-cap	15.3	299.2	38

TABLE 5.2: The maximal 1 MeV neutron equivalent fluences for different parts of the ITk pixel detector. All values have been multiplied by a safety factor of 1.5. Taken from [203].

5.3 Principles of Silicon Pixel Detectors

Progress in particle physics experiments is largely dependent upon the development of sophisticated experimental techniques. Collisions at high energy accelerators produce many different particles, whose identity, direction, and energy are measured using a complex system of complementary sub-detectors. One of the most demanding requirements of a detector such as ATLAS is the micrometer spatial and nanosecond timing resolutions that must be achieved in a hostile radiation environment, close to the interaction point.

The development of both silicon semiconductor devices and microelectronics has enabled modern particle detectors at LHC to feature a highly segmented pixel layer, containing millions of independent, intelligent sensing elements. The introduction of such detectors has allowed detailed studies of short-lived particles, in precise measurements of their decay vertices, and has revolutionised particle detection close to the interaction point. Pixel detectors are also designed to overcome the problem pile-up poses by possessing not only the necessary spatial and timing resolution, but also sufficient granularity to ensure that there is always an available pixel.

The development of silicon pixel detectors in this field is driven by both the desire to study short-lived particles and their ability to cope with ever-increasing rates of interactions, which coincides with the natural progression of modern particle accelerators. Over recent decades, silicon pixel detectors have found a broad range of applications in particle physics experiments. The first experiments to construct a silicon-based tracking detector were the NA11 and NA32 experiments at CERN [212].

The notion of a pixel detector should suggest a matrix of pixels assembled to form an active detection area, where a single pixel is the smallest discernible element. These matrices contain thousands of pixels and cover an area of a few square centimetres. Multiple matrices can then be ‘stitched’ together to instrument large areas. The principle of detection on which they rely is the ionisation of the constituent atoms of the crystal lattice structure of the silicon sample, whereby the passage of a charged particle creates electron-hole pairs (e-h) that are collected through the application of an electric field. Whilst other solid-state sensors exist that are based on the same detection technique, silicon has the advantage that it requires significantly less energy to create an e-h pair, $E_{\text{e-h}}^{\text{Si}} = 3.6 \text{ eV}$, than gas detectors, $E_{\text{e-h}}^{\text{Ar}} = 15 \text{ eV}$. The benefit of this is that for a particle of a given energy, there will be significantly more e-h pairs produced in the silicon detector, which in turn increases the signal to noise ratio [213].

Besides their performance, the fervent interest in silicon pixel detectors is motivated by their radiation-hard properties and relatively low production cost and hence are ideal candidates for large surface tracking in multi-purpose detectors.

Silicon as a Semiconductor

Silicon is an element in group IV of the periodic table and is characterised by four valence electrons in its outermost orbital. Through the formation of covalent bonds, it assumes a diamond lattice structure. Pure silicon is too reactive to be found naturally, and so various crystal growth methods are used to produce ingots of crystalline silicon [214]. The resistivity of the final produced silicon sensors is dependent on the crystal growth technique used, where, for ionising radiation sensors, the resistivity should be large in order to achieve full depletion in a thick substrate at low bias voltages [215, 216].

In solid-state materials, energy levels available to electrons are distributed as closely spaced discrete energy bands, which comes as a consequence of the Pauli exclusion principle that forbids fermions from occupying the same quantum state simultaneously. When covalent bonds form

between two silicon atoms, the energy levels of the electrons slightly shift into separate energy levels, in a process referred to as splitting. Therefore, in a lattice structure with the presence of many atoms, a series of closely spaced energy levels are formed. As a result, two energy bands are created: the *valence band* and the *conduction band*. Charge carriers are bound to the atom in the valence band, whereas they are free within the conduction band. The size of the energy gap, or *band-gap*, between these two bands is what dictates whether the material is an insulator (large band-gap), conductor (no band-gap) or a semiconductor (small band-gap). The theory of this phenomenon is well described by band theory [217], where the band-gap energy is the minimum required energy for an electron to pass from the valence to the conduction band. In the conduction band, the electron is free to move around the silicon lattice and will contribute to the electrical conductivity of the material. In silicon, the band-gap is ~ 1.1 eV, where an average of 3.6 eV is required for an electron to escape a silicon atom since most of the energy is lost within the lattice structure [218].

Once an electron has left an atom, the absence of this negative charge can be thought of as an effective positive charge within the lattice, referred to as a *hole*, which also contributes to the electrical conductivity. As a vacancy appears in the lattice, whereby a hole is created, a neighbouring valence electron can move into this vacancy, and so the hole moves in the opposite direction. Hence, electrons and holes both act as charge carriers and are responsible for the electrical conductivity in semiconductors, unlike conductors, in which the current in the material is only generated by the movement of the electrons. An important parameter related to the movement of the charge carriers is *mobility*, denoted μ , which relates the speed of the electrons and holes and the applied electric field. For electric fields $|\vec{E}| < 10^3$ V/cm $^{-1}$ the mobilities μ_e and μ_h are approximately constant [210].

A semiconductor is referred to as intrinsic if the concentration of impurities in the material is lower than the concentration of thermally generated carriers. This can be calculated from the density of states and the probability of occupation from the Fermi-Dirac distribution by integrating over all valence and conduction band states [217]. The resulting electron (n) and hole (p) concentrations are defined as:

$$n = N_c e^{\frac{E_c - E_F}{kT}} \quad \text{and} \quad p = N_v e^{\frac{E_F - E_v}{kT}} \quad (5.1)$$

where N_c and N_v are the density of states in the conduction and valence bands respectively; k is the Boltzmann constant; T is the temperature and E_F is the Fermi level. For intrinsic silicon, the Fermi level is at an equal distance between the conduction and valence bands, $E_c - E_F = E_F - E_v$, and has equal electron and hole carrier concentrations, $n = p$.

The properties of a semiconductor can be changed by introducing controlled amounts of impurities in a process referred to as *doping*. Despite the small fraction with respect to the density of silicon atoms, where typical doping concentrations range from $10^8 - 10^{12}$ cm $^{-3}$, the introduction of these impurities alters the electrical conductivity of the silicon sample by changing the number of free electrons or holes.

When a group III element, such as boron, is introduced into the crystal structure, it replaces one of the atoms of silicon in the lattice. This atom can accept an electron from a neighbouring silicon atom so that it may bond covalently with its four nearest neighbouring silicon atoms. This creates a hole in the valence band that does not correspond to an electron in the conduction band. The effect of adding boron to the lattice structure is to shift the Fermi level closer to the valence band. This introduces additional holes in the valence band and are referred to as *acceptors*. Hence, this doped silicon is referred to as a *p*-type semiconductor, given the excess of positive charges [217].

Similarly, when a group V element, such as phosphorus, is introduced, it can donate its fifth valence electron to the conduction band, while still having four electrons to bond covalently with the neighbouring silicon atoms in the lattice. This conduction electron does not correspond to a hole in the valence band, and hence the overall number of electrons is increased, and are referred to as *donors*. This shifts the Fermi level closer to the conduction band and are referred to as an *n*-type semiconductor, given the excess of negative charges.

By adding impurities, it is then possible to dictate the majority charge carrier without changing the overall charge of the material. Doping with a significantly higher number of donors $N_D \gg n_i$ causes the material to be *n*-type, where the majority charge carrier is the electron. Whereas introducing additional acceptors so that $N_A \gg n_i$ causes the material to be *p*-type, where the majority charge carriers are holes.

p-*n* Junction as a Particle Detector

The *p*-*n* junction is the fundamental concept of silicon sensors. It is formed when *n*-type and *p*-type silicon is in direct contact with each other. The large carrier concentration gradient at the junction between the two samples causes diffusion of the carriers. Electrons diffuse from the *n*-side into the *p*-side and recombine with the holes that have diffused from the *n*-side. This recombination causes an excess of positive charge close to the border on the *n*-side, and an excess of negative charge close to the border on the *p*-side. These regions of positive and negative space charge consequently create an opposing electric field that is directed from the positive to the negative charge. This electric field counteracts and ultimately prevents the diffusion of more carriers across the junction. The lack of free charge carriers in the region around the junction is a space charge volume [213]. Equilibrium is reached when the potential difference across the junction prevents further charge carriers from moving across the junction. The value of the potential difference is called the *built-in voltage*, V_{bi} . The region immediately around the *p*-*n* junction now has no free charge carriers and as such is called the *depletion region*. The band diagram of the *p*-*n* junction depicting the energy levels is presented in Figure 5.5. The width of the depletion region is represented as w .

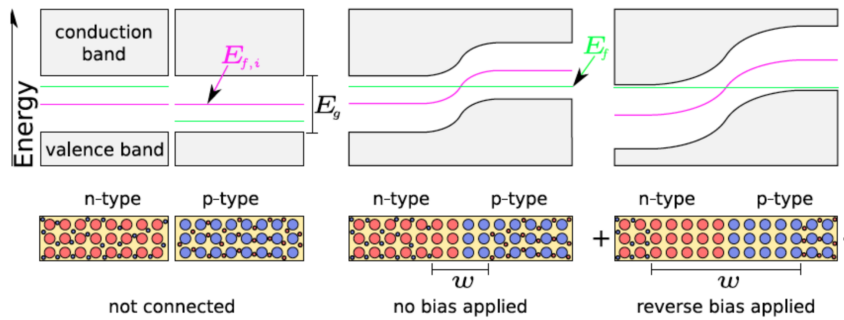


FIGURE 5.5: Illustration of the working principle of the *p*-*n* junction. The upper images show the energy band structure in both *n*-type and *p*-type silicon. The lower images show the acceptors, donors, electrons and holes (large blue, large red, small blue and small red circles respectively) in the doped silicon samples. The width of the depletion region is denoted by w and E_F denotes the Fermi level. Taken from [213].

If an external voltage is applied to the *p*-*n* junction with the same sign as the established V_{bi} (reverse-bias), then the width of the depletion region increases. If, however, a voltage with the opposite polarity is applied to the *p*-*n* junction, then the width of the depletion region decreases [219]. The right diagram of Figure 5.5 shows this increase in the depletion region width after a reverse-bias voltage is applied.

The width of the depletion region can be expressed mathematically as:

$$w = \sqrt{\frac{2 \epsilon_0 \epsilon_{Si} (V_{\text{ext}} + V_{bi})}{q N_{\text{eff}}}} \quad (5.2)$$

Where ϵ_0 is the permittivity of free space; ϵ_{Si} is the relative permittivity of silicon; V_{ext} and V_{bi} are the externally applied and intrinsic built-in voltages; N_{eff} is the effective doping concentration defined as $N_{\text{eff}} = N_D - N_A$. The depletion region can grow until it is the entire thickness of the detector, whereby the sensor is said to be fully depleted. Figure 5.6 depicts typical current-voltage (IV) characteristics of an ideal p - n junction operating under a reverse bias.

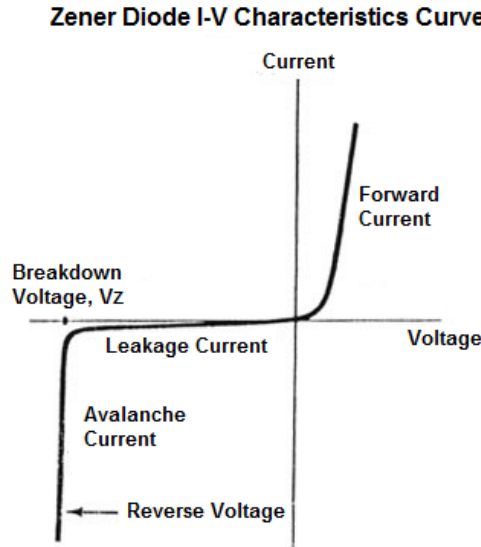


FIGURE 5.6: Typical current-voltage characteristics of an ideal p - n junction under reverse bias. Taken from [250].

In forward bias, when an external voltage is applied, which compensates for the built-in voltage such that $V_{\text{ext}} > V_{bi}$, it causes the current to rapidly increase. This effect occurs when the diffusion current is larger than the drift current. However, when the p - n junction is operated in reverse bias, the current remains very low until it reaches breakdown, where it begins to conduct very large currents. As the reverse bias generates a reverse current, it increases the temperature, which in turn increases the reverse current. This cycle can continue and cause thermal runaway and ultimately causes breakdown. However this can be stabilised by providing external cooling to reduce the reverse current, or by lowering the bias voltage.

The p - n junction constitutes the basic component of a silicon detector, since it can function as a particle detector whilst operated in reverse bias, either fully or partially depleted. Particles that traverse and interact in the depletion region generate e-h pairs. These charge carriers then drift in the applied electric field to either side of the junction. The charge collected at either side of the junction can then be amplified and readout. This functionality can then be segmented, so that the implanted electrodes in the silicon align with the segmented readout in order to provide the required spatial resolution. These pixels are arranged in a two-dimensional array in a grid-like structure, where each pixel has its own associated readout channel.

5.4 Particle Interaction with Matter

Modern particle detectors can be categorised by the underlying detection technique on which they rely. However, they are all dependent on fundamental processes through which particles can interact with the detector material. The interactions of particles relevant to the ATLAS detector are summarised in the following.

Interaction of Charged Particles

The energy loss of a relativistic charged particle with a mass considerably larger than the mass of the electron ($M \gg m_e$) is through interactions with the atomic electrons, whereby a path of e-h pairs is created via ionisation. Examples of these particles are muons, protons and pions. Charged particles mostly interact electromagnetically, where they experience a loss in energy and a deflection of their trajectory. The average amount of energy lost by the particle per unit length is described by the Bethe-Bloch equation [221]:

$$-\left(\frac{dE}{dx}\right) = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (5.3)$$

with:

N_A	Avogadro's number
r_e	classical electron radius
m_e	electron mass
ρ	density of medium
Z	atomic number of medium
A	atomic mass of medium
z	charge of incident particle in units of e
β	relative velocity of incident particle, $\beta = v/c$
γ	Lorentz factor, $\gamma = 1/\sqrt{1-\beta^2}$
$W_{\max}$	maximum energy transfer of single collision
I	average excitation potential
δ	density correction
C	shell correction

The density correction, δ , is an effect that becomes important when the particle is at high energy, where it polarises the material while passing through it. This causes a screening effect on atoms far from the particle and hence reduces the energy loss.

As a function of $\beta\gamma$, the energy loss has no dependence on the mass of the incident particle. The Bethe-Bloch equation is valid in the $\beta\gamma$ range [0.05, 500], whilst other processes become dominant outside of this range. At higher energies, radiative energy loss becomes dominant, for particles such as the muon. Electromagnetic radiation, in the form of bremsstrahlung, is emitted if charged particles are accelerated in the Coulomb field of a nucleus, and is of particular importance for the electron [221].

Figure 5.7 shows the average energy loss per unit length as a function of the $\beta\gamma$ of an incident particle.

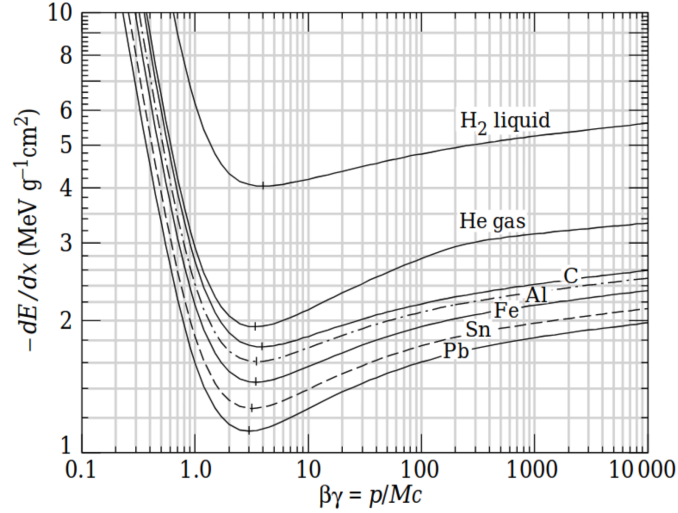


FIGURE 5.7: The Bethe-Bloch equation solved for several materials. Taken from [251].

At non-relativistic energies, the energy loss per unit length is dominated by the $1/\beta^2$ factor and decreases with increasing velocity until approximately $v \sim 0.96c$ [221]. Since there is only a small increase above the minimum, particles in the range $3 < \beta\gamma < 500$ are referred to as Minimum Ionising Particles (MIP), and are commonly produced at the LHC. For increasing energies, the $1/\beta^2$ term becomes approximately constant, where the energy loss per unit length rises due to the logarithmic dependence.

While strong interactions can also occur between charged hadrons, such as protons, they are significantly rarer compared to electromagnetic interactions.

In the case of electrons, the treatment of the stopping power differs given that the mass of the incident particle is comparable to that of the interacting particle in the medium, and hence other processes have to be considered. At low energies, electrons and positrons primarily lose energy by ionisation, however other processes such as Møller scattering and Bhabha scattering contribute. While the ionisation loss rates rise logarithmically, the losses from bremsstrahlung rise almost linearly, where these contributions become dominant around a few tens of MeV [223]. The radiation length, X_0 , characterises the mean distance over which the energy of the particle is reduced by a factor of $1/e$.

Particle Scattering

In addition to inelastic scattering with the atomic nuclei, particles passing through matter can undergo repeated elastic scattering from the atomic nuclei. Given that the mass of the nuclei is usually significantly greater than the mass of the incident particle, the energy transfer is minimal, however each interaction can add a slight deviation to the trajectory of the particle which can become significant. The effect of this can change depending on how many interactions the particle undergoes while traversing the material.

Single scattering occurs when the material is very thin and hence the probability of interacting more than once is negligible. This case is effectively described by the Rutherford formula [224]. When there are several scattering interactions, but it still remains under a few tens of interactions, it is referred to as plural scattering and is notoriously difficult to model effectively [225]. In the case when there is multiple scattering, the angular dispersion can be calculated from the momentum and charge of the incident particle [226]. This effect can be reduced by decreasing

the thickness of the detector material and by using material with a larger intrinsic radiation length.

Interaction of Neutral Particles

Commonly produced neutral particles that contribute significantly to the number of interactions with the detector material are photons and neutrons. Photons can interact with the detector material through different processes dependent upon the energy and on the atomic number of the material:

- **Photo-electric effect:** The most probable process for low energy photons, typically with energy less than 0.1 MeV. An electron is emitted through absorption of a photon with energy greater than or equal to the binding energy of the electron.
- **Compton Scattering:** The most probable process for photons in the energy range 0.1 to 100 MeV. The photon scatters off the electron, transferring some energy in doing so.
- **Pair Production:** The most probable process for high energy photons with energy greater than twice the mass of the electron, > 1.022 MeV. This is the creation of an electron-positron pair.

In the LHC, photons are typically produced with high energy, and hence the dominant process in the ATLAS ID is pair production.

Neutrons can interact with matter via strong interactions with nuclei. The process by which they interact is dependent on the energy of the neutron and on the mass number of the material.

- **Elastic Scattering:** Dominant in the MeV region. Energy is transferred between the incident and target particles, leaving them both intact.
- **Inelastic Scattering:** Occurs at energies greater than approximately 1 MeV. The nucleus is excited and decays through the emission of a photon.
- **Neutron Capture:** Dominant process for low energy neutrons with approximate energies in the eV-keV range. Following the interaction $n + (Z, A) \rightarrow \gamma + (Z, A + 1)$.

5.5 Signal Formation

When traversing a silicon sensor of thickness $200\ \mu\text{m}$, a minimum ionising particle releases $1.66\ \text{MeV cm}^2/\text{g}$, corresponding to approximately 16000 generated e-h pairs. This is a crucial quantity when deciding the threshold in the electronics. The collected signal is not the direct collection of the charges on the electrode, and is instead created by the time-varying change in potential on the electrodes that is induced by the drifting charge carriers. This effect is modelled by the Shockley-Ramo theorem [220].

This induced signal is required to be amplified and digitised in order to be transmitted to the data-acquisition system. This is performed on a dedicated readout chip, which is typically composed of an analogue and a digital circuitry. In hybrid designs, the readout chip is commonly segmented to match that of the pixel geometry and is connected to the sensor via bump-bonding.

The FE electronics is composed of three distinct components: a pre-amplifier, a feedback circuit and a discriminator. The induced current, Q_{in} , at the electrode is converted into a voltage pulse

by a charge sensitive amplifier, where the converted signal height is proportional to the energy of the incident particle. Figure 5.8 presents a schematic diagram of the operating principles of a charge sensitive amplifier. The choice of the feedback capacitance, C_f , is crucial to the FE design, whereby it is related to the output voltage with $V_{\text{out}} = Q_{\text{in}}/C_f$. This is true in an ideal condition of infinite gain, however in reality the gain is finite and a residual voltage originating from the internal and detector capacitances is measured at the input. This residual voltage impacts the output voltage of the amplifier, hence the choice of feedback capacitance is therefore designed to reject the noise coming from the amplifier, while considering the gain, power consumption and time response. The feedback capacitor of the charge sensitive amplifier needs to be reset after a signal from the sensor has been processed to avoid a pile-up of pulses. This is achieved by adding either a resistor or constant current source in parallel with C_f . The slope of the discharge function can then be tuned by global and local digital to analogue converters (DACs) through the feedback circuit [210].

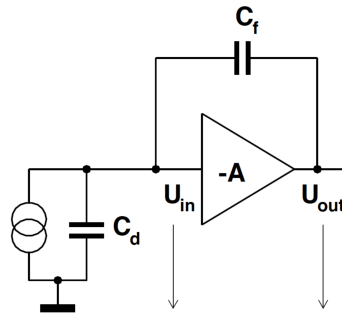


FIGURE 5.8: Simplified schematic diagram of a charge sensitive amplifier. The silicon sensor is represented by a current source in parallel with the overall detector capacitance C_d . Taken from [210].

Given the large number of channels that large surface tracking detectors utilise, the analogue signal is required to be digitised. The output signal of the charge sensitive amplifier is then passed to a discriminator, which imposes a threshold in order to select signals which are large enough to have originated from a particle hit, whilst removing signals originating from noise. The threshold is therefore directly related to the minimum amount of charge needed to acknowledge the presence of an incident particle, and therefore to the detection efficiency. The value of this threshold is set as low as possible to ensure high signal acceptance, while also rejecting signal from noise. This parameter is controlled by dedicated DACs. A global tune, setting the overall threshold used at sensor-level, and a local tune, to optimise each parameter pixel by pixel, can be applied.

After imposing this threshold, the time that the signal remains above the threshold, referred to as time-over-threshold (ToT) is then proportional to the height of the signal. Figure 5.9 illustrates graphically how this is performed. The ToT is therefore an effective measurement of the collected charge on the sensor and thus the deposited energy of the incident particle [210].

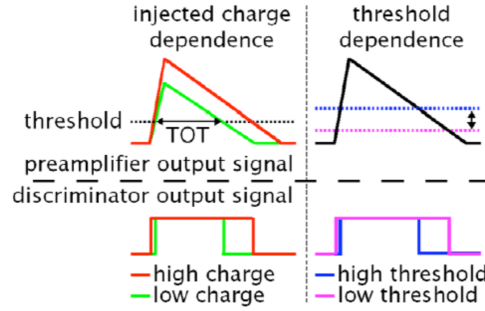


FIGURE 5.9: Comparison of the relationship between the preamplifier signal and the discriminator output signal for changes in the injected charge and threshold. Taken from [222].

5.6 Radiation Damage in Silicon Pixel Detectors

The energy loss of particles in silicon pixel detectors can be categorised into ionising energy loss and non-ionising energy loss (NIEL). The latter causes defects to appear in the crystal lattice since the lattice atoms are displaced. Particles that traverse the detector degrade the lattice through hadronic interactions and cause defects in the lattice that are electrically active and can affect the conductivity of the material. Electrons in the conduction band or holes in the valence band can be trapped and recombine. Silicon atoms that are removed and receive a sufficient amount of kinetic energy can remove other atoms from the lattice, creating a cascade of interactions and producing a cluster-effect of damage. These radiation induced lattice damages can be categorised as either point or cluster defects. Whilst the NIEL primarily affects the silicon bulk of the sensor, the ionising energy loss particularly affects the dielectric (often SiO_2) interface that is commonly used to electrically passivate the sensor surface. The high rate of particles produced in LHC interactions induce damages to the silicon pixel detectors, which manifests as an increase in the leakage current, a considerable change to the required depletion voltage and a decrease of the charge collection efficiency. Along with the degradation of the FE electronics, this poses one of the most important operational challenges of the ATLAS ID [214].

Depending on the particle type, it will interact through different processes and cause radiation damage in different ways. Neutrons release the maximum NIEL since they only interact via inelastic scattering. Slow charged hadrons mostly interact electromagnetically, so little of the energy loss contributes to the creation of cluster defects. However, faster charged hadrons are able to produce substantially larger cluster defects. A simulation of the radiation damage caused by neutrons, and low and high energy protons is shown in Figure 5.10.

Non-Ionising Energy Loss

NIEL is defined as the amount of energy that is deposited into the material by an incident particle that is not due to ionisation. Given that different particles produce differing effects while releasing NIEL, they are therefore first normalised to the equivalent NIEL of a 1 MeV neutron in order to effectively compare them.

The defects that are created in the crystal lattice of the silicon bulk significantly alter the properties of the detector. These defects introduce additional energy levels in between the conduction and valence bands, which can then act as either generation or recombination centres. Levels that are introduced at similar distances to either band, electrons and holes follow similar access probability. In contrast, bands that form closer to either conduction or valence band act as trapping centres. This trapping causes the effective doping concentration, N_{eff} , of the material

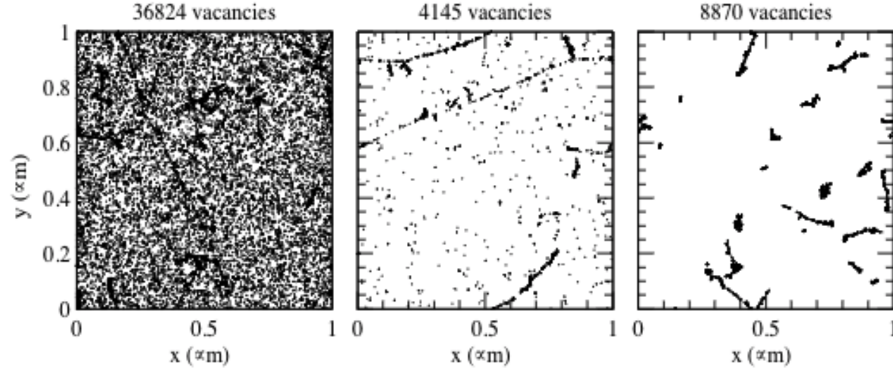


FIGURE 5.10: Simulation of defect formation caused by the passage of different types of irradiating particles. Left: 10 MeV protons. Centre: 24 GeV protons. Right: 1 MeV neutrons. Taken from [227].

to change, since mobile charge carriers are removed from the material, and hence directly affects the depletion zone and the required depletion voltage to reach full depletion. It is typical that the experiments at the LHC that utilise planar pixel sensors are required to increase the depletion voltage as the received dose increases over time [210]. The effective doping concentration can be formulated as:

$$N_{\text{eff}} = \frac{2 \epsilon_0 \epsilon_{Si} V_{\text{depl}}}{q t^2} \quad (5.4)$$

Where V_{depl} is the required bias voltage to achieve full depletion and t is the thickness of the sensor. It has been shown that when starting with n -type silicon, the effective doping concentration decreases until it actually changes sign, so it is dominated by acceptor-like defects as shown in Figure 5.11 [210]. This process is referred to as *space charge inversion*.

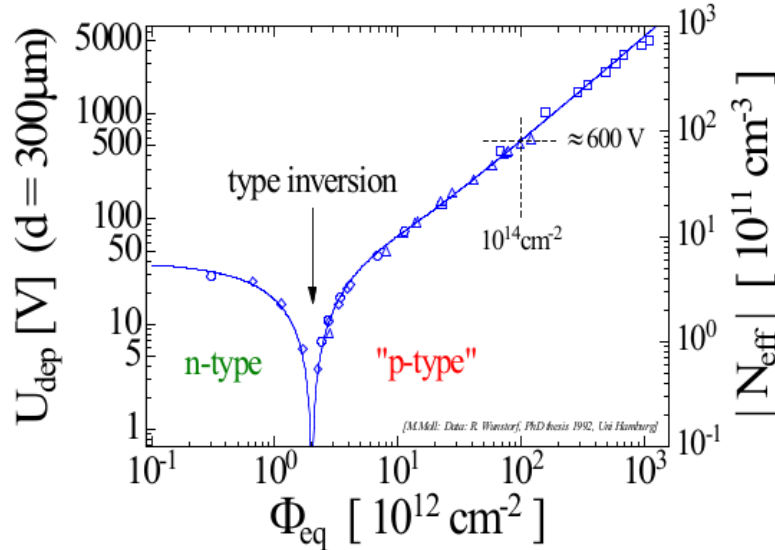


FIGURE 5.11: Evolution of the full depletion voltage of a 300 μm thick silicon sensor and its absolute doping versus the normalised fluence. Taken from [252].

This charge trapping also has an effect on the measured signal, since the trapped charge carriers are released with a delay in the order of μs , and is substantially longer than the data-taking time

window, where the LHC collision rate is 25 ns. The total signal that is measured is therefore less than for un-irradiated devices and as a result reduces the detector performance.

Since the energy bands are shifted closer to the conduction and valence bands, the thermal activation of an e-h pair becomes significantly more probable and hence the leakage current in the silicon bulk increases. This effect can be reduced by introducing dedicated cooling to decrease the thermal activation in the silicon bulk.

The evolution of the effective doping concentration with the fluence is well modelled using the so-called Hamburg-model [214]. This is a phenomenological model that provides accurate predictions of the properties of silicon pixel detectors after irradiation and plays a crucial role in the construction and operation of the ATLAS ID.

With the development of silicon sensor technologies fabricated in a low resistivity substrate, such as the HV-CMOS technology, a novel effect, previously not yet described by the Hamburg-model was observed. Initially observed in TCT² and laboratory measurements [253], the *acceptor removal mechanism* exhibits an increase in depletion depth with increasing irradiation. This phenomenon is interpreted as an effective decrease in the number of acceptors in the *p*-type silicon bulk of the sensors and was found to be correlated to the initial resistivity of the substrate, such that for a high-resistivity substrate it becomes negligible, as presented in Figure 5.12. The mechanism describing the rate of acceptor removal depending on the initial substrate resistivity is still to be understood.

The presented studies contain some of the first evidence of the acceptor removal mechanism observed during beam test measurements. These studies are documented in Section 5.9.

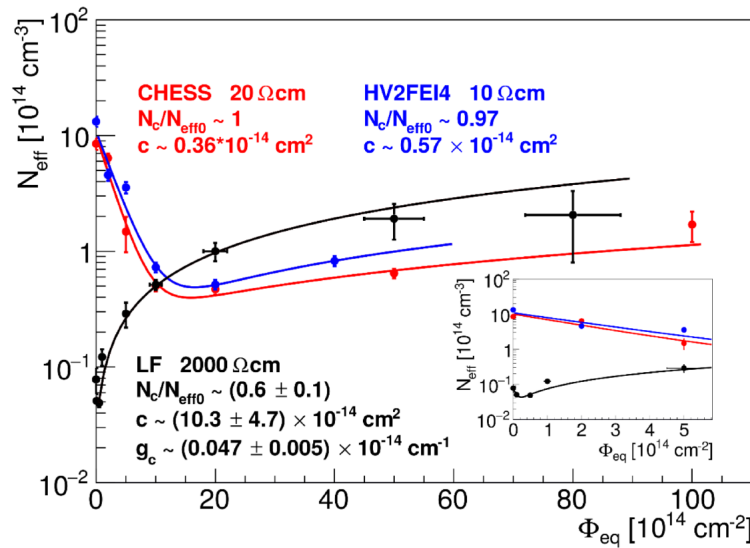


FIGURE 5.12: Effective doping concentration as a function of radiation fluence for three devices with different initial resistivities. Taken from [253].

Ionising Energy Loss

Whilst the NIEL typically affect the bulk of the silicon substrate, the ionising energy loss mostly affects the silicon-dielectric boundary. As previously stated, the dielectric material is commonly SiO₂ and is commonly referred to as the oxide layer. The dose of ionising energy loss is typically expressed in Rads, corresponding to $6.4 \cdot 10^{10}$ MeV of ionising energy deposition per kilogram

²Transient Current Technique.

of material. As an ionising particle traverses the material, it generates e-h pairs in the oxide layer. Since the electrons have a high mobility ($\mu_n^{\text{oxide}} = 20 \text{ cm}^2/(\text{Vs})$), they are quickly collected. Holes, however, have a significantly lower mobility ($\mu_p^{\text{oxide}} = 2.0 \cdot 10^{-5} \text{ cm}^2/(\text{Vs})$) as a result of the large density of shallow hole traps present in the oxide lattice. The holes tunnel from one trap to another in the direction of the electric field until they reach the silicon-oxide interface. This positive charge collects and creates a fixed positive charge in the dielectric [228].

5.7 Monolithic CMOS Pixel Developments

The HV-CMOS technology was originally designed for use in electronic ASIC chips responsible for driving automotive or industrial devices and is well suited for use in a wide variety of applications. Given its commercial availability, the manufacturing process allows for a low-cost and low-material assembly of silicon detectors, and thus poses an interesting option for large area tracking systems. An investigation into the potential use of the technology is being pursued by many high energy physics experiments such as ALICE, CLIC and Mu3e, as well as the ATLAS collaboration.

The HL-LHC project represents a unique challenge given the unprecedented levels of required radiation tolerance and timing resolution to meet the foreseen LHC operating conditions. Whilst proven hybrid technologies will instrument the inner layers of ITk, the HV-CMOS technology is of particular interest for the outermost pixel layer, where there is an expected fluence of $1.5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$. In this region, the requirements of the radiation tolerance and event rate are reduced and hence offers an opportunity to introduce and test a developing technology.

Whilst hybrid technologies have a silicon sensor with an associated readout chip, monolithic technologies would see the inclusion of the sensor and required electronics into one chip. The monolithic CMOS technology could allow the device to provide the necessary charge collection, analogue amplification stage, and digitisation process in a single silicon wafer. The most striking implication of such a technology would be to the production process, whereby the previously necessary bump-bonding process is no longer needed, which drastically reduces the cost and complexity of production. However, it could also potentially reduce the power consumption and the material needed to instrument the tracking system. Assessing the performance of these detectors within the high radiation and high rate environment is one of the subjects of the presented thesis, where the following Chapter contains a study performed during beam test measurements.

The operating principle of the HV-CMOS sensor is founded on a multi-layered structure, where multiple nested wells provide sufficient isolation between the bias voltage and the embedded transistors used to process the signal on-chip. A schematic figure of the overall HV-CMOS sensor design is presented in Figure 5.13. The sensors consist of a thin p -type silicon bulk, which contains a deep n -well that is designed to host the in-pixel electronics. The deep n -well provides sufficient shielding for the transistors from the potential in the p -type substrate, whilst also acting as the collection electrode. Since the transistors do not ‘see’ the potential within the substrate, a large reverse bias can be applied without damaging the transistors. In this way, a depletion zone is created on the diode formed by the deep n -well and the p -substrate, where the deep n -well acts as the potential minimum for electrons, and hence the charge collection occurs by drift. The HV-CMOS pixel sensors considered in this thesis are fabricated in a typical resistivity of $\sim 10 \Omega \cdot \text{cm}$, approximately two orders of magnitude lower than the sensors currently used by the ATLAS detector. The bias voltage is applied through a p -implant located on the top surface of the device. The sensor is then operated with a bias voltage of the order of 80 V, whilst breakdown occurs at around 100 V. The corresponding depletion depth is around $10 \mu\text{m}$.

A minimum ionising particle passing through the silicon would release around $80 e^-/\mu\text{m}$, assuming a perfect collection efficiency of the drift charges, which equates to around $800 e^-$ collected. This value is low relative to the typical threshold imposed by hybrid pixel sensors of $2000 e^-$. The CMOS sensor is therefore produced to contain an in-pixel amplification stage that amplifies the signal to a sensible value. HV-CMOS sensors that contain full readout electronics are monolithic, whilst hybrid sensors that are instead coupled after the amplification stage to a readout chip by a layer of glue are referred to as a *Capacitively Coupled Pixel Detector*, or CCPD. This on-chip amplification stage allows for the use of AC-coupling, where the sensor can be simply glued to the FE-I4 readout chip instead of having to use bump-bonding. In conventional hybrid

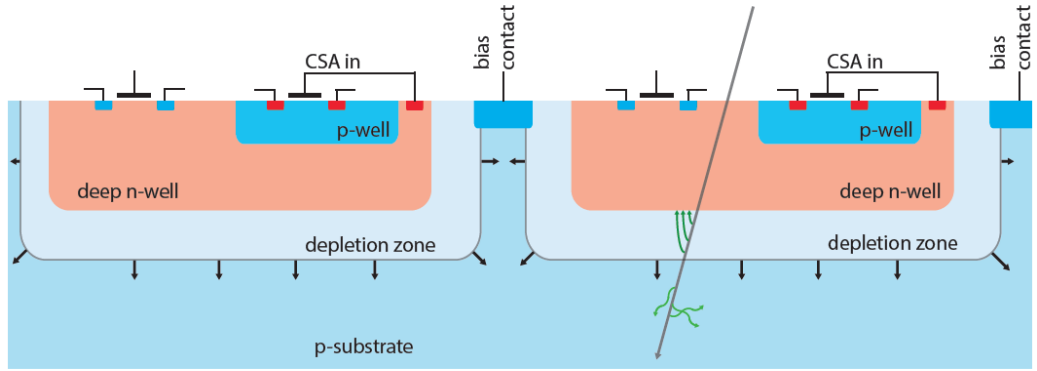


FIGURE 5.13: Illustration of working principle of two neighbouring HV-CMOS pixels. For each pixel a deep n -well (in light red) is imbedded in the p -substrate (in light blue) and hosts the NMOS transistors. PMOS transistors are imbedded in the p -well (in bright blue), which is isolated from the bulk by the deep n -well. p -implants provide a biasing ring around individual pixels. An ionising particle traversing vertically through the detector is also depicted, where the charge deposition is represented to be collected by drift in the depletion zone close to the deep n -well and by diffusion in the deep bulk. Taken from [208].

pixel assemblies, the dimensions of the pixel is constrained by the minimum size required for the bump-bonding process. Since this process is not required in CMOS sensors, the pixel size can be made to be much smaller. This in turn leads to improved spatial resolution with a higher granularity. This is of particular importance given the high track density environment expected at the HL-LHC.

This technology also provides a large *fill factor*, where the relative area of the collection electrode is large, hence there are no low field regions in the bulk and ensures short drift distances. Due to the high electric field and the low resistivity of the substrate, charge collection is fast, and the sensor is nearly insensitive to radiation-induced trapping. Given that this trapping effect contributes dominantly to the overall degradation of sensor performance by NIEL, these sensors are expected to exhibit high radiation tolerant properties. As well as a high radiation tolerance of the silicon bulk, the deep sub-micron technology itself that is implemented in the sensors is also expected to be highly radiation tolerant [229].

The studies presented in this thesis focus on the performance of CCPD devices. Whilst these are an interesting option in their own right, they share the same sensor design as the desired fully monolithic sensor, and hence the same charge collection techniques. The CCPD devices are therefore used as a way of testing the performance of the sensor before a full monolithic implementation.

H18CCPDv4

The CCPDv4 is the fourth revision of HV-CMOS pixel sensor prototypes using the AMS H18 process in 18 nm technology [230]. These sensors have a total size of $\sim 2.4 \times 2.9 \text{ mm}^2$, with a thickness of $250 \mu\text{m}$ and a substrate resistivity of $10 \Omega \cdot \text{cm}$. Figure 5.14 shows the overall CCPDv4 assembly.

The prototypes feature four different pixel flavours, where each type has a slightly different on-sensor electronics. The characterisation presented focuses on the *STime* pixel on the HV-CMOS sensor. Each *STime* pixel has a size of $33 \times 125 \mu\text{m}$ and contains an amplifier and a discriminator

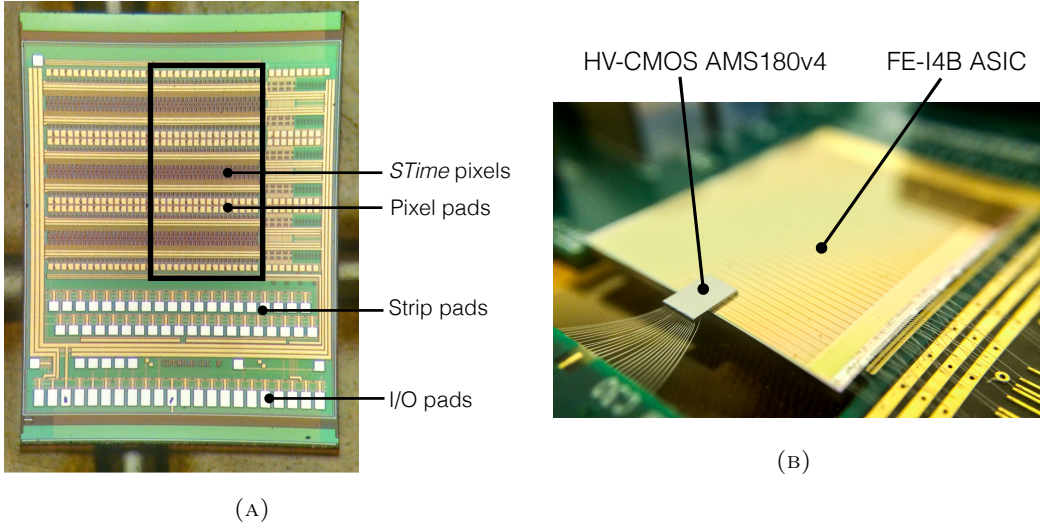


FIGURE 5.14: Left: Photograph of the CCPDv4 sensor used in the presented study, where the sub-matrix of STime pixels is indicated. Right: Assembly of FE-I4 pixel readout chip to a HV-CMOS CCPDv4 sensor via capacitive coupling [239].

together with a 4-bit in-pixel DAC. As depicted in Figure 5.15, this DAC allows for a threshold tune of each individual pixel.

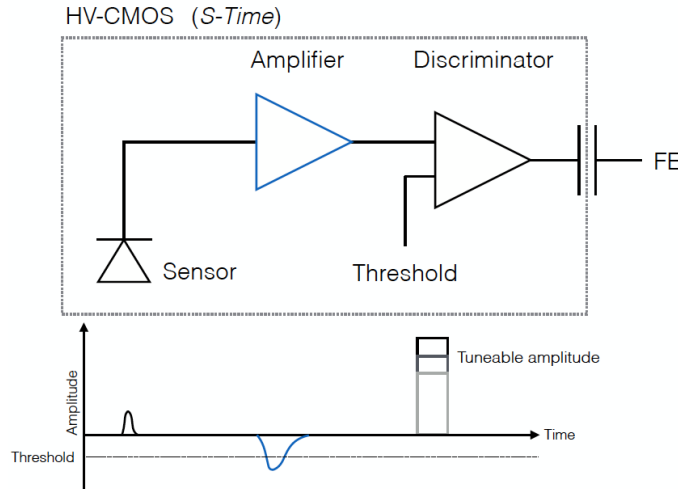


FIGURE 5.15: Schematic representation of the electronics contained in the chip. The sensor is shown as a diode that is connected firstly to a charge sensitive amplifier followed by a discriminator with a tunable threshold. The output signal is then capacitively connected to the FE-I4 [239].

The CCPDv4 sensors are glued to the FE-I4 readout chip using Araldite non-conductive epoxy glue, where the sensor electrodes and the input pads of the readout channels form capacitors. This capacitive coupling then allows the FE-I4 to readout the digital signal from the sensor. In order to match the pixel size (pixel pitch) of the FE-I4, $50 \times 250 \mu\text{m}^2$, the HV-CMOS pixels are grouped into sets of three, forming two $100 \times 125 \mu\text{m}^2$ macro-pixels as is shown in Figure 5.16. Therefore, a unit cell consisting of six HV-CMOS sub-pixels (each $33 \times 125 \mu\text{m}^2$) connected to two FE-I4 pixels (each $50 \times 250 \mu\text{m}^2$) is formed. Whilst it is possible to distinguish between

these sub-pixels, the signal amplitude of the discriminator output of each of the three sub-pixels was set to the same voltage level for simplicity during beam test measurements.

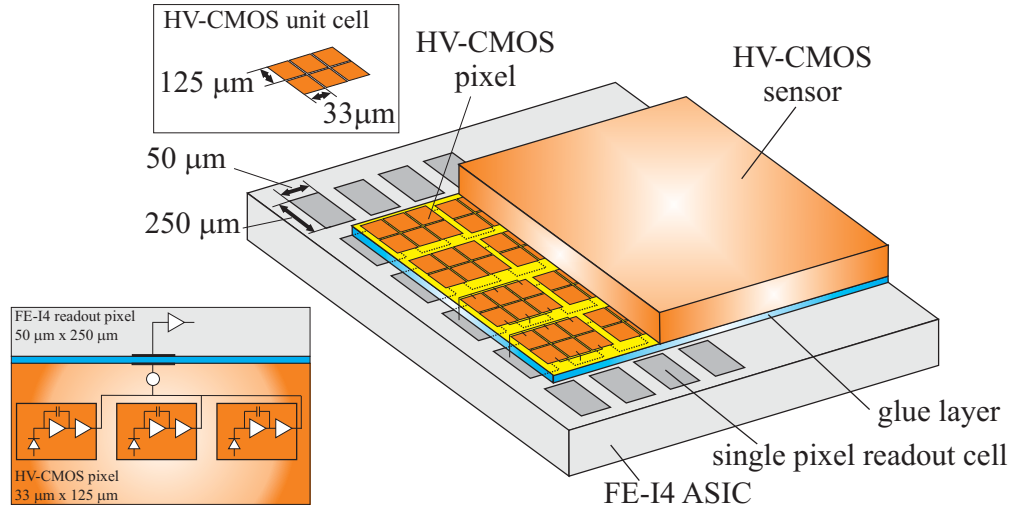


FIGURE 5.16: Schematic representation (not to scale) of the HV-CMOS CCPDv4 sensor connections to the FE-I4. The bottom-left inset shows how three HV-CMOS pixels (forming a so-called macro-pixel) are capacitively coupled to a single FE-I4 readout pixel [239].

H35 Full-Size Demonstrator Prototype

Following the small-scale CCPDv4 prototype, a large-scale pixel sensor prototype was produced. The H35 Demonstrator is produced in AMS H35 350 nm technology as a full scale $24.4 \times 18.5 \text{ mm}^2$ chip, with a pixel pitch of $50 \times 250 \mu\text{m}^2$ in order to match to the FE-I4. The demonstrator is divided into four independent matrices: two monolithic matrices, integrating either CMOS or NMOS readout circuitry; and two analogue matrices containing a per-pixel amplification stage, which is then capacitively coupled to the FE-I4. Figure 5.17 depicts the layout of the H35 Demonstrator chip, indicating the approximate areas of each of the matrices.

Within each of the analogue matrices, there are different sub-matrices, each designed to test slight design variations of the on-pixel electronics. The first analogue matrix consists of circuitry containing different transistor technologies, either linear or enclosed layout (ELT), and different p -wells, either with or without an additional deep p -well (DPTUB), used for applying a bias voltage. The second analogue matrix also contains three types of pixel, exhibiting different gain from the in-pixel amplifier and different p -wells for high voltage biasing, as in the first analogue matrix. The design features of these sub-matrices is summarised in Table 5.3.

	Analogue Matrix 1	Analogue Matrix 2
sub-matrix 1	Extra DPTUB + ELT	Extra DPTUB + high gain
sub-matrix 2	No DPTUB + ELT	No DPTUB + high gain
sub-matrix 3	No DPTUB + linear transistor	No DPTUB + low gain

TABLE 5.3: Summary of sub-matrix design features of the H35 Demonstrator analogue matrices.

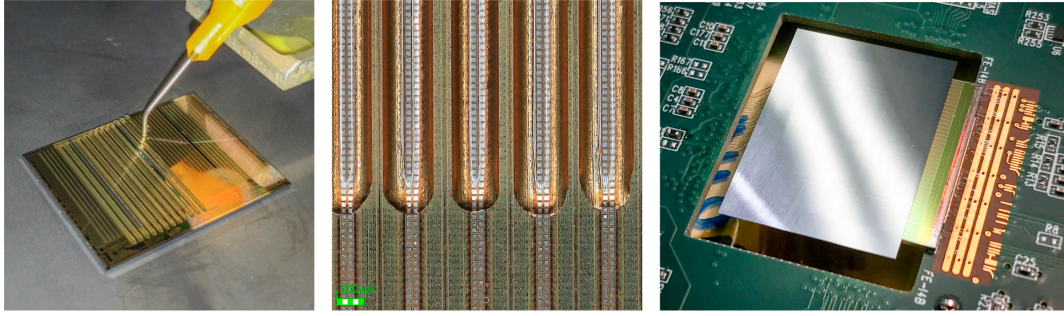


FIGURE 5.19: Left: Deposition of epoxy on the H35 Demonstrator matrix. Middle: glue (partially) deposited on double pixel column. Right: Full assembly of 100 μm thin H35 Demonstrator sensor with FE-I4 on PCB. [246].

Throughout the characterisation, H35 Demonstrator prototypes were produced at different resistivities of 20, 80, 200 and 1000 $\Omega \cdot \text{cm}$ and were studied in beam test measurements.

FE-I4 readout Chip

The FE-I4 readout chip contains 26,880 pixels arranged in an array of 80 columns and 336 rows. It is produced in a 130 nm feature size bulk CMOS process, with a pixel size of $50 \times 250 \mu\text{m}^2$. The pixel size of the FE-I4 is smaller than its predecessor and hence improves the hit resolution and also lowers the pixel hit occupancy.

The FE-I4 features an active area almost 90% larger than the FE-I3 and contains significantly more digital functionality. The inclusion of this additional digital circuitry means that an additional module controller chip that was present in the detector during Run 1 is no longer required. The larger active area of the FE-I4 allows for a simpler design with respect to the FE-I3, which ultimately reduces the material used to instrument the detector. The data storage of the FE-I4 is implemented at pixel-level until triggering has been propagated to the pixel array. Each pixel contains an amplification stage, where the registered hits pass to a discriminator that imposes a threshold, converting the information on the charge collected into a ToT. Technical information about the FE-I4 can be found in Ref. [91, 231].

5.8 Experimental Setup and Reconstruction

Readout System and the FE-I4 Telescope

In order to test the manufactured HV-CMOS sensors, a dedicated test system is required to perform laboratory characterisation and beam test measurements. The modular test system that is used is the CaRIBOu (Control and Readout ITk BOard) system [232] and was initially designed and developed for use with CCPD devices, however it can be adapted for different sensors. The FE assembly is composed of the CaR (Control and Readout) board and the FE chip board, as is shown in Figure 5.21. The CaR board is designed to provide configuration and readout to the device under test (DUT) and controls the power supply, bias voltages and pulse injections. The FE chip board is designed to house the DUT, where the CCPD devices being tested are wire-bonded to the board. Figure 5.22 presents an image of the CaRIBOu readout system during a beam test measurement at the CERN SPS facility.

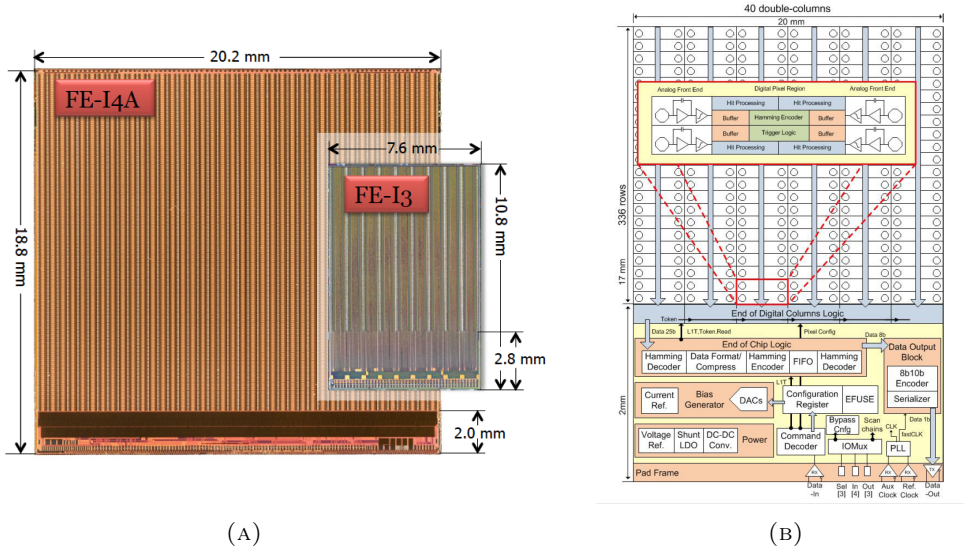


FIGURE 5.20: Left: Illustration of the FE-I4 in comparison to its predecessor, the FE-I3. Right: Schematic view of the FE-I4 readout architecture [91].

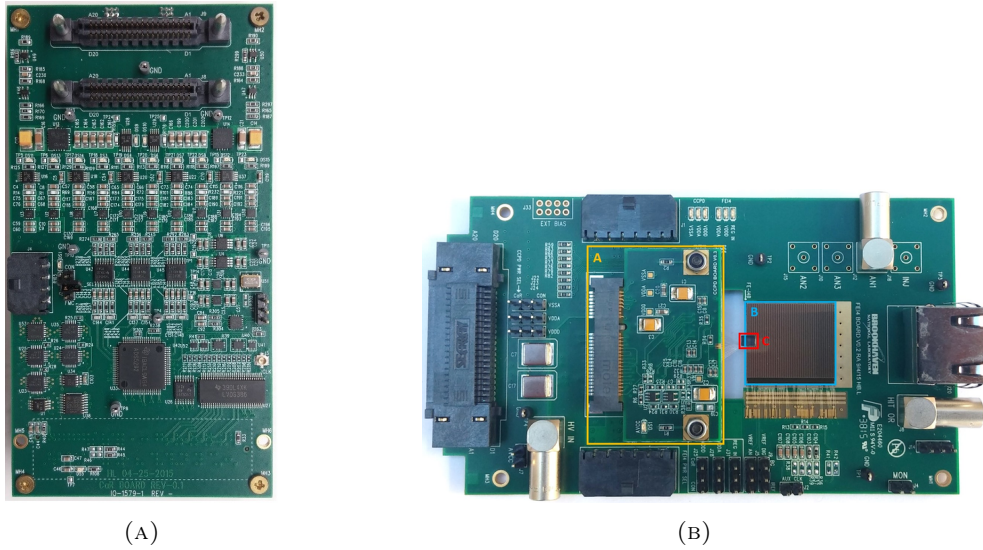


FIGURE 5.21: Left: Image of the CaR board. Right: Image of the FE chip board, where the CCPDv4 sensor can be seen coupled to the FE-I4, with wire-bond connections to the PCB.

Due to differences during production, the effective threshold of each pixel can differ compared to the global value provided by the CaR board to the HV-CMOS sensor that could potentially lead to a pixel-by-pixel mismatch. Given the comparatively low threshold imposed in the HV-CMOS sensors, a uniform effective threshold is vital in order to achieve an overall high detection efficiency and to reduce noise. This is of particular significance when the sensor is irradiated. A pixel by pixel tune on the threshold is possible through the local TDAC value of each individual pixel as part of the in-pixel discriminator. Pulse injections can be sent to the devices from the CaR board, where the known signal charge is injected several times as input to the amplifier. The percentage of signal over threshold is computed and the injected charge is altered until the rate over threshold reaches 100%. Thermal and statistical effects in the sensor cause this to be an S-curve, opposed to the ideal step-function. This procedure is repeated for differing TDAC values until the optimal value is achieved.

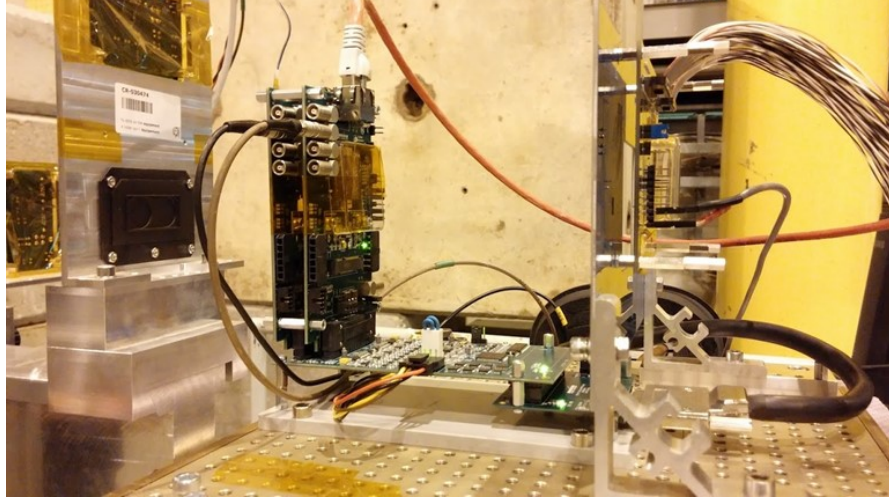


FIGURE 5.22: Image of the CaRIBOu readout system during beam test measurements at the CERN SPS facility.

After the devices are initially characterised in a laboratory, it is essential to evaluate their performance when exposed to high energy particles. Beam test measurements are performed where the detection efficiency of the DUT is compared to a well understood charged particle tracking telescope. The FE-I4 telescope [233] has been successfully operated during the beam test campaigns at the CERN SPS and at the Fermilab beam test facilities. Figure 5.23 presents a rendered image of the FE-I4 beam telescope.

The FE-I4 telescope is composed of two aluminium arms, each supporting three planar pixel sensors readout by the FE-I4 chip. As the pixel size is not equal in the two axes orthogonal to the beam direction, $50 \times 250 \mu\text{m}^2$, the middle planes on both arms are rotated by 90° so that the pointing resolution is comparable in both axes. Each detection layer is glued to a modular PCB adaptor board, which is responsible for providing the necessary powering and operation during measurements. The DUT is located in between the arms of the telescope and is positioned on a mechanical stage capable of micrometer adjustment for appropriate alignment. The high irradiation levels received by the devices necessitates a dedicated cooling system to reduce the thermal noise induced by shallow traps in the silicon bulk. This is enacted through the baseplate of the stage, where it is connected to an external chiller and can be cooled to -50°C . To prevent condensation from damaging the electronics, cold nitrogen is used to flush the box and temperature and humidity sensors are used to monitor the environment during measurements.

A Detector Control System (DCS) based on LabView is used to remotely control the required high and low voltage power supply to the telescope planes and to the DUT, whilst also controlling the power supplies for the chiller and the motorised stages. It also monitors the humidity and temperature sensors at the DUT. The data acquisition (DAQ) system is based on a High Speed I/O (HSIO) board and the Reconfigurable Cluster Element (RCE) [234] and is capable of collecting data from the six telescope planes and up to two DUTs. The HSIO board is a general purpose readout board that is responsible for relaying commands from the RCE and for the collection and distribution of the data. It is also responsible for providing the global clock and the trigger to the telescope plane and the DUT [233]. The RCE board is responsible for the processing, sending and receiving of the data [235].

The trigger system is based on the self-triggering functionality of the FE-I4 and is then centrally controlled by the HSIO. A coincidence trigger between the first and last telescope planes is used to generate a trigger, if they both register a hit within a time window of 25 ns, corresponding to the LHC bunch crossing. This trigger is then delivered to the DAQ system where it is redistributed.

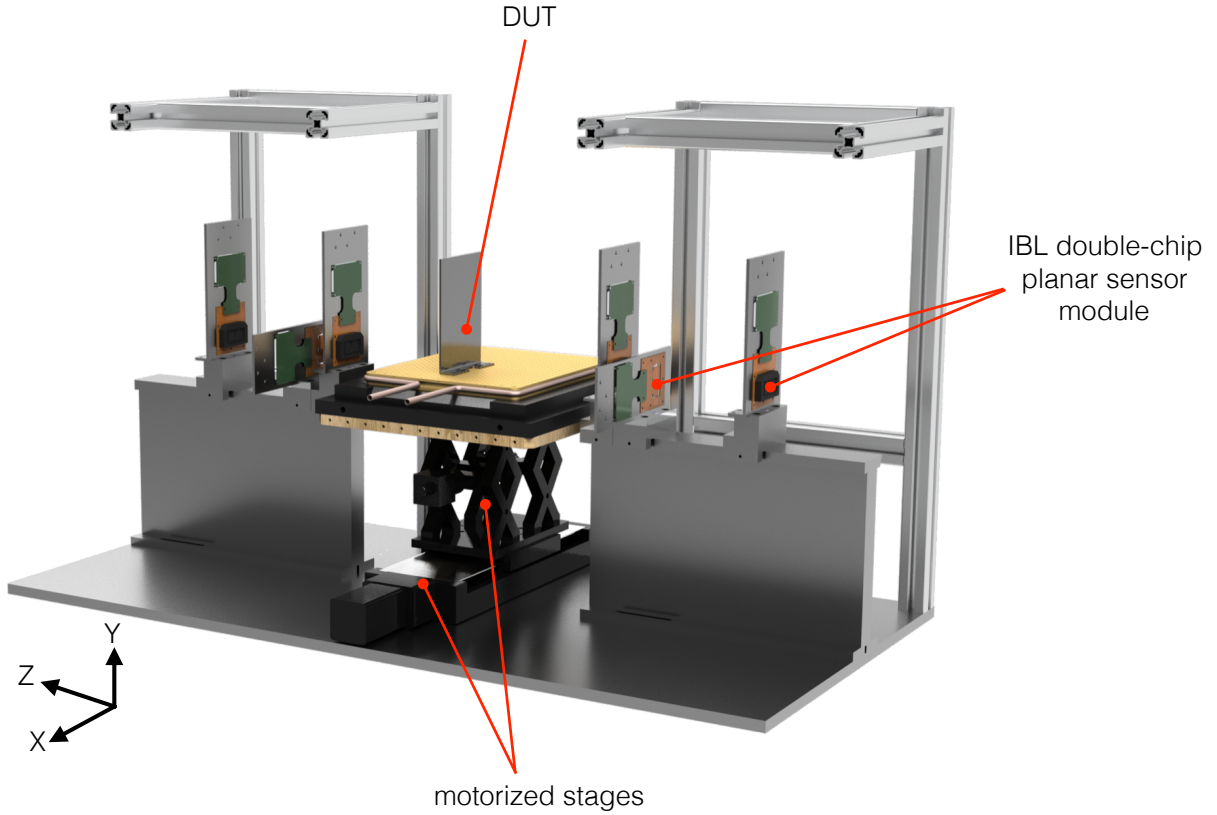


FIGURE 5.23: A rendered image of the FE-I4 beam telescope. The coordinate system is defined with the z -axis along the beam-axis, the y -axis pointing vertically upwards and the x -axis pointing horizontally [233].

The telescope planes that are used to trigger are configured so that only a specified sub-set of the pixels are used, thus defining a region of interest, which is of particular use during measurements of the small-scale CCPD $v4$ prototypes. This allows for a considerable reduction in data events that are triggered, but do not pass through the DUT. After each trigger, a defined timing window is specified during which the data from the telescope planes and DUT is readout in order to fully characterise the device in terms of timing performance. This window is defined in terms of the number of LHC bunch crossings (BC), to provide a comparable unit. The DUT is readout for 16 BC after the trigger, while the telescope planes are readout for 4 BC to reduce the data transferred to the readout system.

The offline reconstruction software used to analyse beam test measurement data that was originally based on the Judith framework [236] has been significantly improved over the course of the studies presented in the thesis, and the analysis software is now based on is known as the Proteus framework [237]. The following describes the reconstruction algorithms that were used during the data analysis of the presented results.

The main processes involved in the reconstruction are to initially isolate and locate hits in the detection layers individually. These hits are assembled into groups within each of the planes to form a cluster, which are then matched to one another across the detection layers so as to reconstruct a track of the incident particle. The potential misalignment of the detection planes is corrected in a dedicated procedure. The hit efficiency of the DUT is calculated as the detection rate compared to the expected rate by comparison to the reference telescope planes. Taking into account the telescope geometry and the pixel granularity, the telescope resolution is estimated to be $\sigma_x = 11.7 \mu\text{m}$ and $\sigma_y = 8, 3 \mu\text{m}$.

Clustering Algorithm

Depending on the pixel size, a single or multiple pixels may register a hit when an incident particle traverses the detector. This will depend on the point where the particle crosses, the angular offset between the beam direction and the sensor orientation. Figure 5.24 illustrates the different cases.

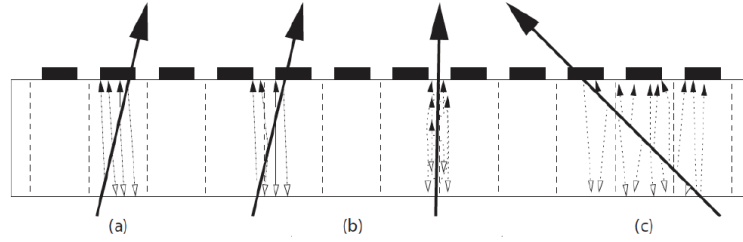


FIGURE 5.24: An illustration depicting how the incident particle direction and location on the detection surface could lead to a different number of pixels firing. (a) shows a single pixel firing; (b) shows two cases of how a single particle can cause two pixels to fire; and (c) shows three pixels firing. Taken from [210].

A clustering algorithm is designed to collectively identify neighbouring pixels that register a hit and group them together to form a single particle hit. The cluster is formed by iterating through the registered pixel hits and forming groups of neighbouring pixels, where a cluster has to form a complete area and will not encompass clusters with ‘holes’ in the formation. This process is repeated for all registered hits in the detection surface that are previously unassociated to a cluster.

When a cluster is identified in the pixel layer, its position is determined by calculating the barycentre from the x and y coordinates of each of the pixels forming the cluster. The cluster size refers to the number of neighbouring pixels that register a signal above threshold and form the cluster. The cluster size distribution is directly related to the charge sharing between the pixels. Whilst most clusters are only one pixel, there is an asymmetric cluster geometry observed for a cluster size of two, which comes as a consequence of the asymmetric dimensions of the FE-I4 pixels, leading to more charge sharing between pixels in the shorter pixel-pitch direction.

Tracking Algorithm

Once the clusters have been identified in each of the detection planes, a tracking algorithm is implemented to reconstruct the track of the incident particle. The tracking algorithm is a two-step procedure: track finding algorithm, designed to identify the clusters associated to the candidate track hypothesis; and the track fitting, where a fit is performed in order to obtain the optimal parameters describing the candidate track. Typically, noise hits and hits originating from overlapping events pose the most difficult challenges during track reconstruction, however due to the low noise rate of the FE-I4 readout chip and the short timing window used during data taking, the algorithm can be simple yet efficient.

The tracking algorithm takes a seed cluster from the first telescope plane and searches for clusters in the consecutive planes based on a defined cone angle with respect to the initial seed cluster. It is initially assumed that the track is perpendicular to the surface of the planes, however this becomes iteratively corrected as additional clusters are selected and added to the track. If multiple candidate clusters are found on a plane, then the track bifurcates and further searches continue for each of the clusters. Clusters that are already associated to a track are removed from the iteration. Candidate tracks with the largest number of clusters are kept, given that there is a cluster in all six of the telescope planes. The high energy of the particle beams produced

at the SPS and Fermilab beam test facilities allow to confidently neglect the effects of multiple scattering, hence allowing the algorithm to fit the track with a straight line. The straight line fit is performed and the candidate track with the smallest χ^2 is chosen. Detailed information can be found in Ref. [233].

One of the most significant parameters is the residual distribution, defined as the difference between the position that the reconstructed track intercepts the plane and the position of the cluster used to form the track:

$$\text{Res}(u) = u_{\text{track}} - u_{\text{cluster}} \quad \text{Res}(v) = v_{\text{track}} - v_{\text{cluster}} \quad (5.5)$$

where u and v are the coordinates in the system of the plane. Since the reconstruction of the track is dependent on the cluster in question, the cluster is removed from the track fitting procedure in order to present an unbiased result. The RMS of such a distribution is a measure of the resolution of the sensor.

Alignment Procedure

In a tracking system instrumented with highly segmented pixel detectors, small offsets and rotations can cause misalignment and so the relative position between detector planes of the telescope need to be accurately known. Starting with the positions and rotations of the planes, the two-step alignment procedure is applied to correct for lateral misplacement and rotation about the z -axis.

An initial coarse alignment procedure calculates 2D inter-plane hit correlation distributions, by comparing the cluster positions, using the first plane as a reference. It is assumed that the beam is perpendicular to the telescope planes, which should yield a straight line in the reconstruction. Given a perfect alignment, the beam would pass through the origin with a slope equal to the ratio of the pixel pitches. This assumption is later accounted for in the subsequent process. Shifts between the planes are therefore identified from the offset of the line from the origin and the rotation from the differences of the measured to the calculated slopes. A Gaussian is fitted to the distributions and the mean is extracted and used to shift the planes in the x - and y -axis. The first plane is used as reference, where each subsequent plane is adjusted to its neighbour.

In a second step, a fine alignment uses the track residuals for the precise positioning of the planes, as the distance between the reconstructed track position and the position of the associated cluster for each plane. The correction is calculated from the difference between the residual and the hit position for each plane. Since the track position is affected by the current misalignment of each of the planes, the plane being aligned is omitted from the track fitting procedure and hence uses unbiased track reconstruction [233].

5.9 Beam Test Results

Beam test measurements are performed in order to assess the performance of the DUT through the hit efficiency and timing characteristics. By comparing the position of the tracks expected at the DUT with the cluster position detected at the DUT, the hit efficiency can be determined. In these studies, the pixel detector response is compared to the telescope using a defined ellipse. The interpolated track is expected to pass through the ellipse centred around the measured cluster. The ellipse is defined with the major and minor radii equal to one and a half times the pitch of the macro-pixel and is depicted in Figure 5.25.

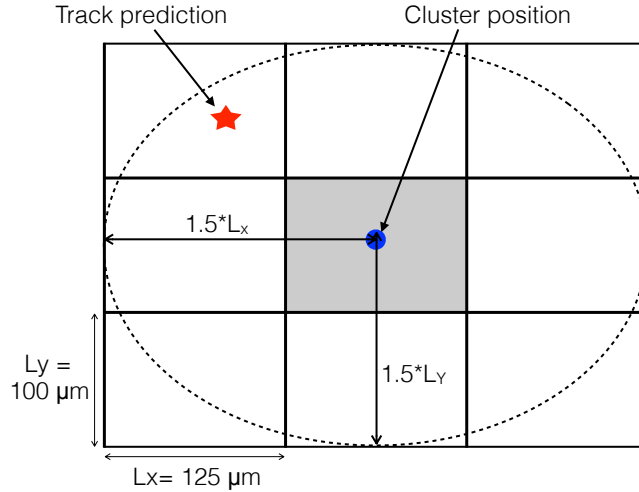


FIGURE 5.25: Area used to calculate the hit efficiency. Each $125\,\mu\text{m} \times 100\,\mu\text{m}$ macro-pixel (shown in grey) is formed by three single HV-CMOS pixels [239].

The per-pixel efficiency is defined in Equation 5.6 as the ratio between the number of clusters in the DUT that match the reconstructed tracks from the telescope and the number of well reconstructed tracks that are predicted to pass through the DUT within its active area.

$$\epsilon = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{expected}}} \quad (5.6)$$

In the following Section, the beam test results of timing efficiency performance of irradiated CCPDv4 and un-irradiated H35 Demonstrators will be presented.

H18CCPDv4 Results

Following from the promising results of a characterisation of the un-irradiated CCPDv4 [238], research and development (R&D) efforts towards the characterisation of these devices after irradiation was performed, to mimic the foreseen HL-LHC environment [239]. The samples were irradiated using reactor neutrons at the TRIGA reactor in Ljubljana [240] and 18 MeV protons at the Bern Cyclotron Laboratory [241–243]. The samples were irradiated to fluences between $1 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$ and $5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ in steps chosen to emulate the increase over the lifetime of the ITk outer-pixel layer.

The normalised residual distributions of the DUT irradiated to $1 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ are shown in Figure 5.26. The distributions in both the x - and y -axis are centred around zero, showing a good alignment in both directions. The RMS of the distributions are compatible with the

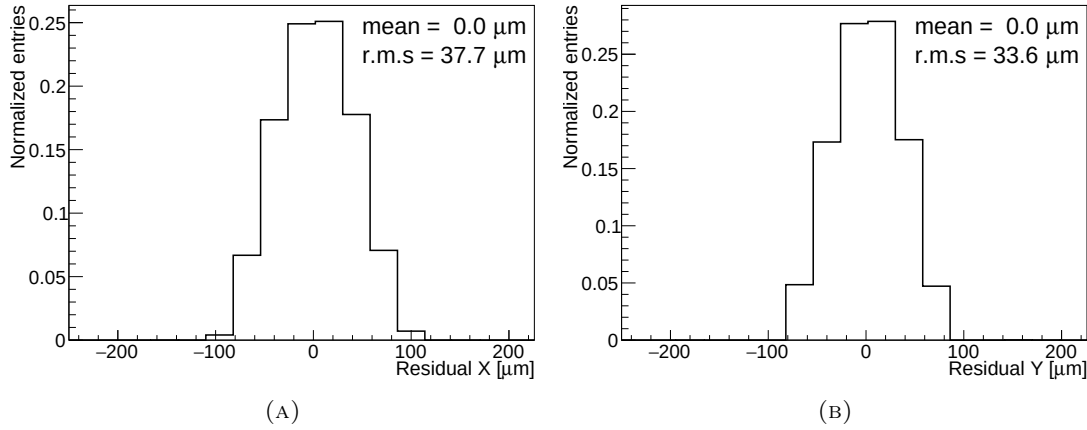


FIGURE 5.26: Normalised residual distributions of the DUT irradiated to $1 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ in the x - and y -axis [239].

expected intrinsic resolutions of the macro-pixel when a single hit is detected in the cluster: $\sigma_x = 125/\sqrt{12} = 36.1 \mu\text{m}$ and $\sigma_y = 100/\sqrt{12} = 28.9 \mu\text{m}$.

Table 5.4 presents the cluster size for each of the samples at varying amounts of irradiation. The diffusion component previously observed during un-irradiated measurements [238] is reduced since the radiation damage introduces shallow traps that reduce the charge sharing effect and, in turn, the cluster size. All of the irradiated samples show that the majority of the detected clusters have a size of one.

Fluence [$n_{\text{eq}}/\text{cm}^2$]	0	$1.3 \cdot 10^{14}$	$5 \cdot 10^{14}$	$1 \cdot 10^{15}$	$5 \cdot 10^{15}$
CS = 1	0.783	0.970	0.958	0.978	0.961
CS = 2	0.196	0.028	0.038	0.020	0.034
CS ≥ 3	0.020	0.002	0.004	0.002	0.004

TABLE 5.4: Cluster size fractions for different fluences [239].

An average efficiency of 99.7% was measured at both sample- and pixel-level. The efficiency distributions of the neutron-irradiated samples are shown in Figure 5.27, presenting both the sample-level distribution on the left, and the sub-pixel on the right. A more effective representation of the pixel hit efficiency distribution is through histograms, which allow to more intuitively identify outliers, for example due to defective sub-pixels. Figure 5.28 shows the efficiency histograms for the samples irradiated to increasing doses. An average efficiency of 98.1, 99.7, 99.7 and 97.6% are found for the samples irradiated to $1.3 \cdot 10^{14}$, $5 \cdot 10^{14}$, $1 \cdot 10^{15}$ and $5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ respectively. These values are excellent and are comparable to the results of planar sensors, where it is typical of detectors to require hit efficiencies $> 97\%$ after irradiation [244]. Outlying events can be observed in the efficiency distribution of the $5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ samples. These are most probably originating from pixels with damaged circuits from the considerably high irradiation, however the fluence of this samples is five times larger than the maximum expected fluence in the outermost pixel layers of ITk.

Bias voltage and threshold scans were performed in order to characterise the performance for various working points during the operation of the DUTs. The efficiency as a function of the bias voltage and threshold are presented in Figures 5.29 and 5.30.

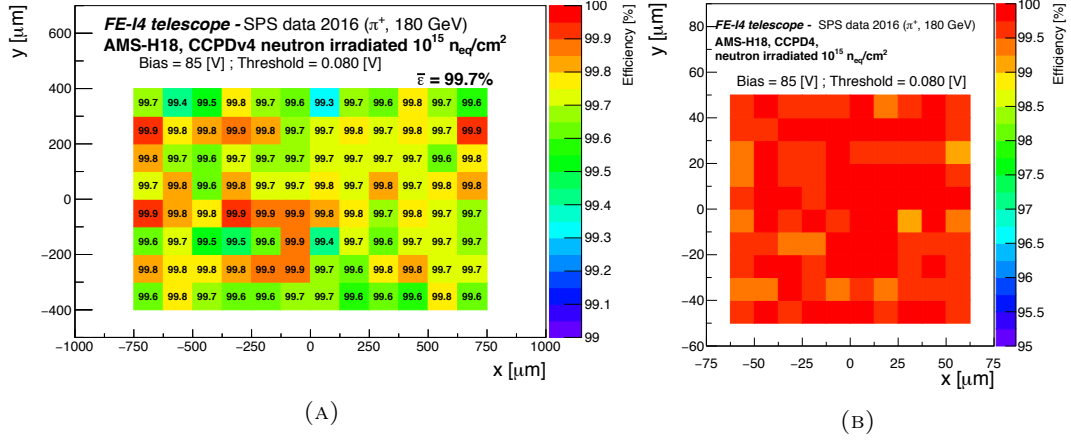


FIGURE 5.27: A) Hit efficiency map for CCPDv4 neutron irradiated with $1 \cdot 10^{15} n_{eq}/cm^2$
 B) Sub-pixel hit efficiency map overlaid from all central pixels. No significant efficiency loss is visible in any region of the pixel.

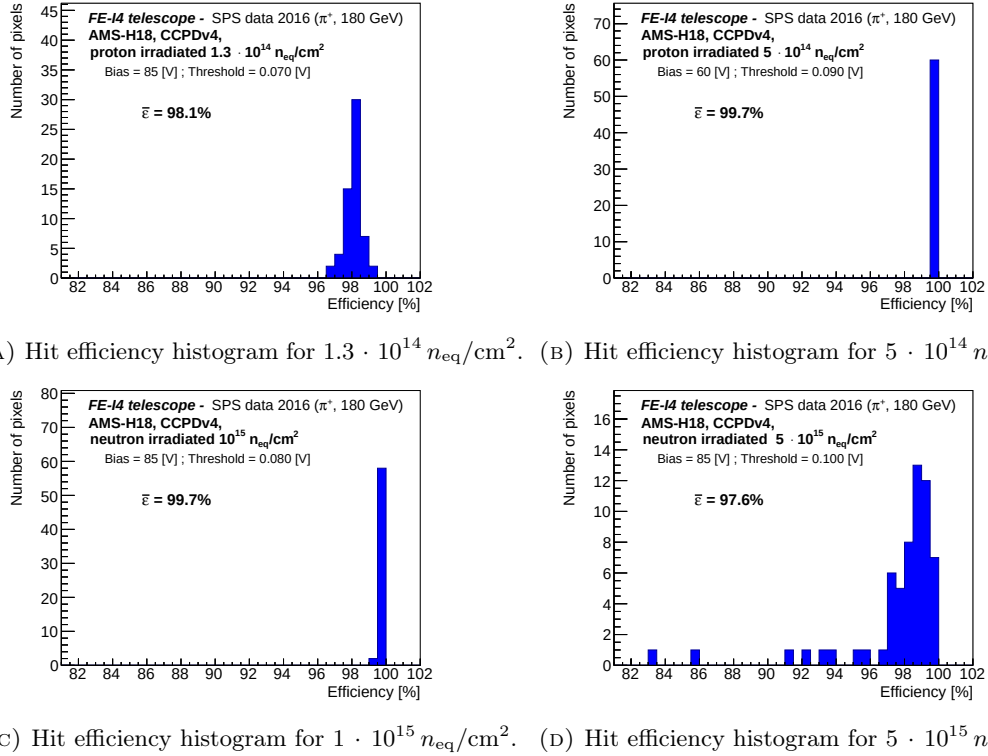


FIGURE 5.28: Hit efficiency histograms for different fluences of protons (upper row) and neutrons (lower row) [239].

The bias voltage scan reaches a plateau after approximately 40 V for the majority of the irradiated sensors, where in particular the low and high fluences benefit from a maximum voltage close to breakdown at around 85 V. This effect is caused by an operational feature of the HV-CMOS sensors, where, contrary to planar sensors, they do not need to be operated in maximum depletion and so the increase in bias voltage compensates for the loss in efficiency with increasing fluence. For the intermediate fluences the extension of the depleted region is already sufficiently large so as to not require large bias voltages and comes as a consequence of the acceptor removal effect. The sample irradiated to the highest fluence, $5 \cdot 10^{15} n_{eq}/cm^2$, is found to produce the highest levels of noise, in particular at a bias voltage of 85 V and hence the observed decrease in

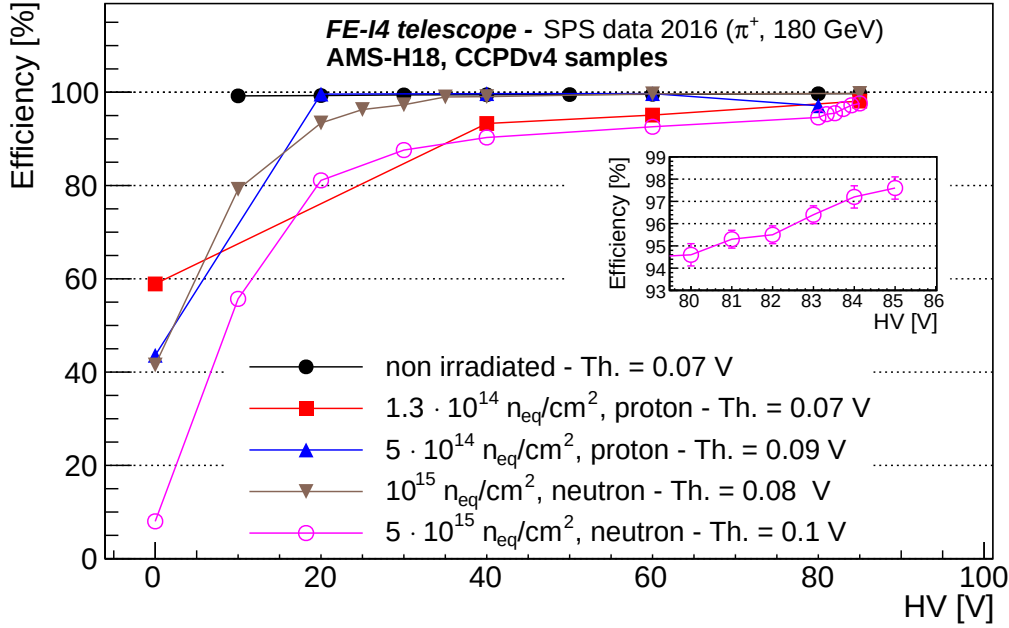


FIGURE 5.29: Average hit efficiency as a function of the bias voltage. The inset presents the increase in efficiency between a bias voltage of 80 and 85 V for the highest irradiated sample [239].

efficiency at this operating point. By comparison to the samples irradiated to $5 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$ and $1 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$, the sample that received the lowest fluence, $1.3 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$, exhibited a decrease in efficiency. This is caused by an initial reduction in the collected charge due to the loss of diffusing charge carriers not yet alleviated by the increase in depletion depth caused by the acceptor removal effect. The sample that received the largest fluence shows an increase in efficiency at large bias voltages. This is attributed to charge multiplication effects, whereby the high density of traps caused by the significant radiation damage along with the high electric field causes further impact ionisation from the primary ionisation [245].

With increasing thresholds, there is a loss in efficiency due to the low charge signals not being detected, as seen in Figure 5.30. This effect is not particularly prominent for the highest irradiated sample, which may be attributed to the higher depletion depth at this amount of radiation damage. At low thresholds, the noise becomes dominant and the efficiency decreases. Intermediate threshold values show a plateau that is more obvious than for the other fluences, whilst the lowest and highest fluences suffer a decrease in the observed signal caused by either the small depletion depth or increased trapping, which ultimately decreases the width of the plateau.

The HL-LHC ATLAS tracker will need to cope with up to 200 pile-up events every 25 ns and so it is essential that it is able to identify the tracks and assign them to the correct BC timing window. The timing distribution of each of the irradiated samples is presented in Figure 5.31. Nearly all of the events are collected within one timing bin, where 95% of the charge is collected within 3 BCs for all fluences that have been tested. The acceptor removal effect is also evident as the collection time improves for increasing fluences. The $5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ shows a decrease in the time resolution that is most likely caused by the higher threshold and hence less charge collected.

Figure 5.32(a) presents the timing distribution of a CCPDv4 device for four different bias voltages: 0, 40, 60 and 85 V. Figure 5.32(b) shows the average timing of an event depending on

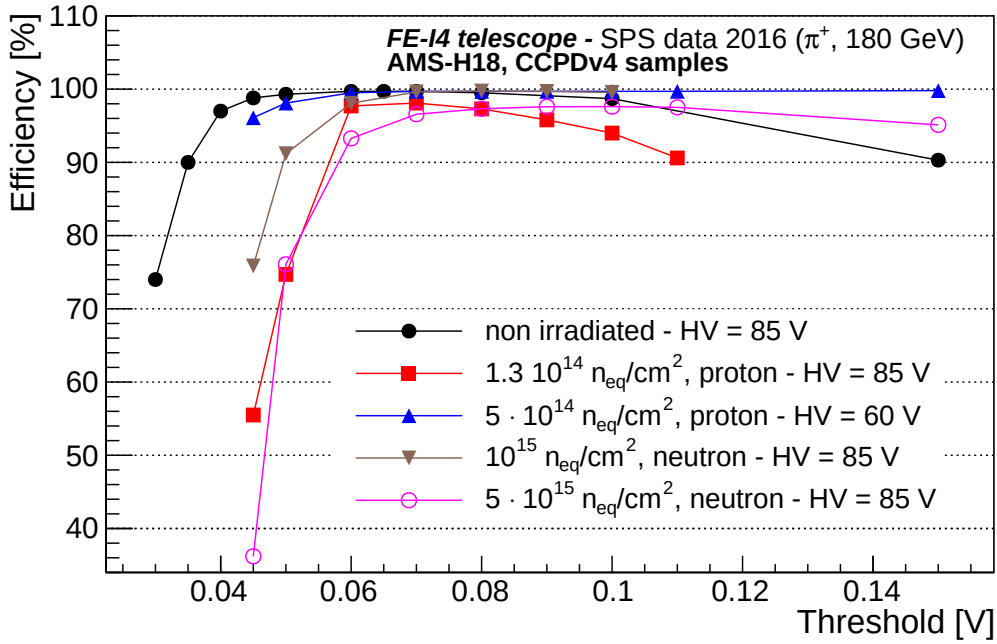


FIGURE 5.30: Average hit efficiency as a function of the threshold [239].

the track position within the pixel. Intuitively, the timing distribution corresponding to a 0 V bias voltage shows events are slow with a broad range of timing. As the voltage increases, the timing resolution improves since the increasing electric field causes faster charge collection. The in-pixel mean timing map suggests that events detected in the centre of the pixel, below or near the collection electrode, are collected faster, while the events registered at the edges of the pixel are generally slower in collection. The CCPDv4 sensor is biased only from the top-side, and not from the back-side, which leads to regions of lower electric field strength and explains the slower charge collection observed at the horizontal edges.

H35 Demonstrator Results

The performance of the irradiated CCPDv4 samples provided excellent results, showing high efficiency and fast charge collection. Following from these results, the full size H35 Demonstrator device was tested at the Fermilab beam test facility and at the CERN SPS facility using 120 GeV protons and 180 GeV pions respectively. To characterise the efficiency and timing resolution of different substrate resistivities, samples with four different resistivities: 20, 80, 200 and 1000 $\Omega \cdot \text{cm}$ were produced and tested through beam test measurements. The breakdown voltage of the majority of the resistivities was measured to be around 170 V [246]. Compared to the CCPDv4 devices, the pixel size matches that of the FE-I4, $250 \times 50 \mu\text{m}$, and hence no sub-pixel encoding is required. This allows for removal of the discriminator from the in-pixel electronics and couple the amplifier output directly to the FE-I4, allowing for a direct ToT measurement.

As previously described, the H35 Demonstrator features different sub-pixel matrices implementing differences in in-pixel electronics and pixel sub-structure, summarised in Table 5.3. The measurements presented were taken using only the Analogue1 and Analogue2 matrices. Table 5.5 summarises the parameters used during measurements of the H35 Demonstrators.

The cluster size distributions for different resistivities and bias voltages are presented in Figure 5.33. The majority of the clusters measures a single pixel, since the pixel size is significantly

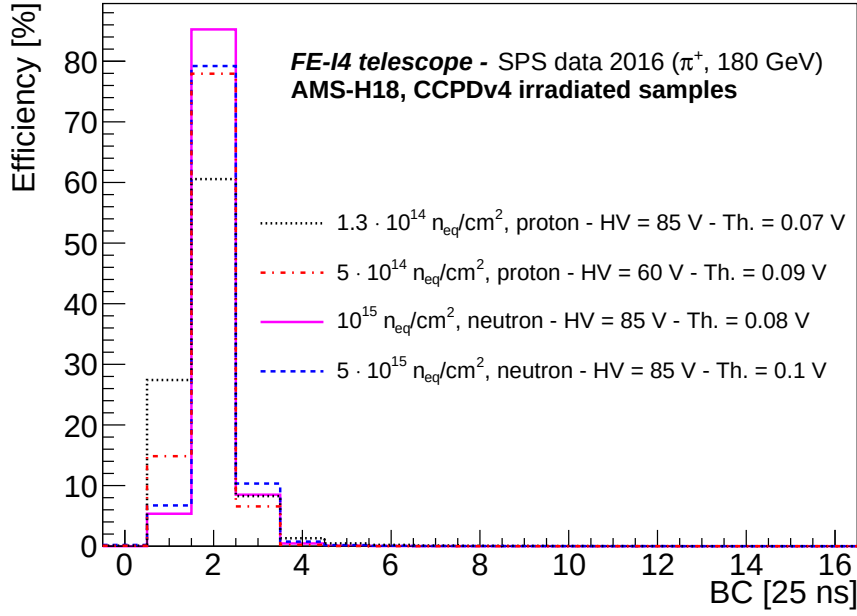


FIGURE 5.31: Timing distributions for the four irradiated CCPDv4 samples at the operational bias voltages [239].

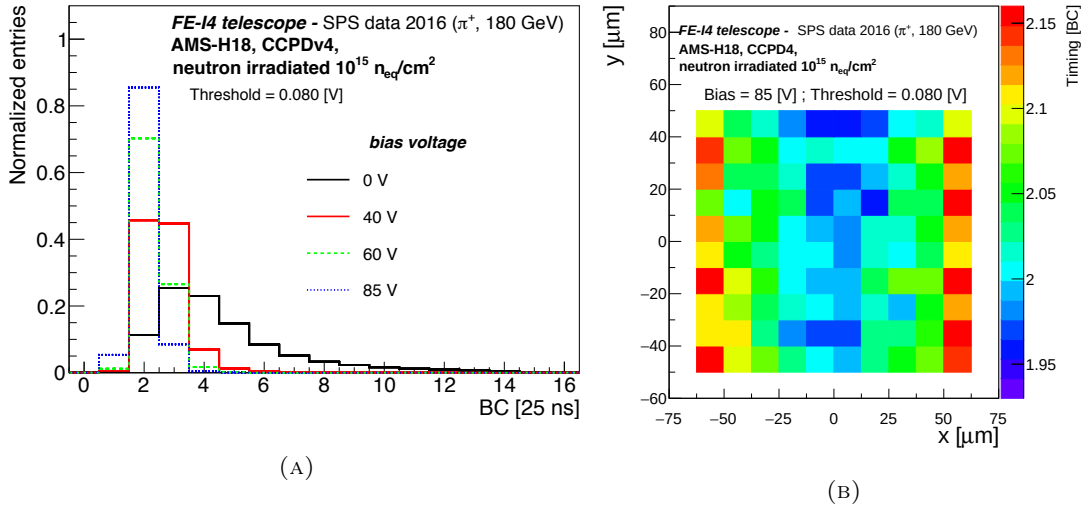


FIGURE 5.32: A) Timing distribution for a CCPDv4 device for four values of the bias voltage. B) In-pixel timing map showing the mean timing of the event for the track position inside the pixel [239].

larger than that of the CCPDv4 devices. The magnitude of the bias voltage becomes more important for higher resistivity samples, where in particular the $1000 \Omega \cdot \text{cm}$ sample exhibits effects of competing mechanisms within the sensor. The charge deposited deeper in the bulk will drift for a longer time than the charge close to the collection electrode. With increasing bias voltages, the collection time decreases. Since the bias voltage is applied via an n -well on the top of the sensor, as the depletion depth becomes larger than the distance between the electrode and the n -well, the behaviour of the diode diverges from that of a planar diode and causes a region of weak electric field strength, and hence there is an increase in cluster size for intermediate voltages [246].

Resistivity [$\Omega \cdot \text{cm}$]	Matrix	Bias Voltage [V]	Threshold [ke]
20	Analogue1	0-160	1.5, 2
80	Analogue1	0-160	2.5, 3, 4
200	Analogue2	0-140	2, 2.5, 3, 4
1000	Analogue1	0-160	1.5, 2, 2.5, 3

TABLE 5.5: Summary of parameters used for H35 Demonstrator beam test measurements. The FE-I4 threshold represents the signal being transferred from the capacitive injection, instead of the real charge generated on the sensor [246].

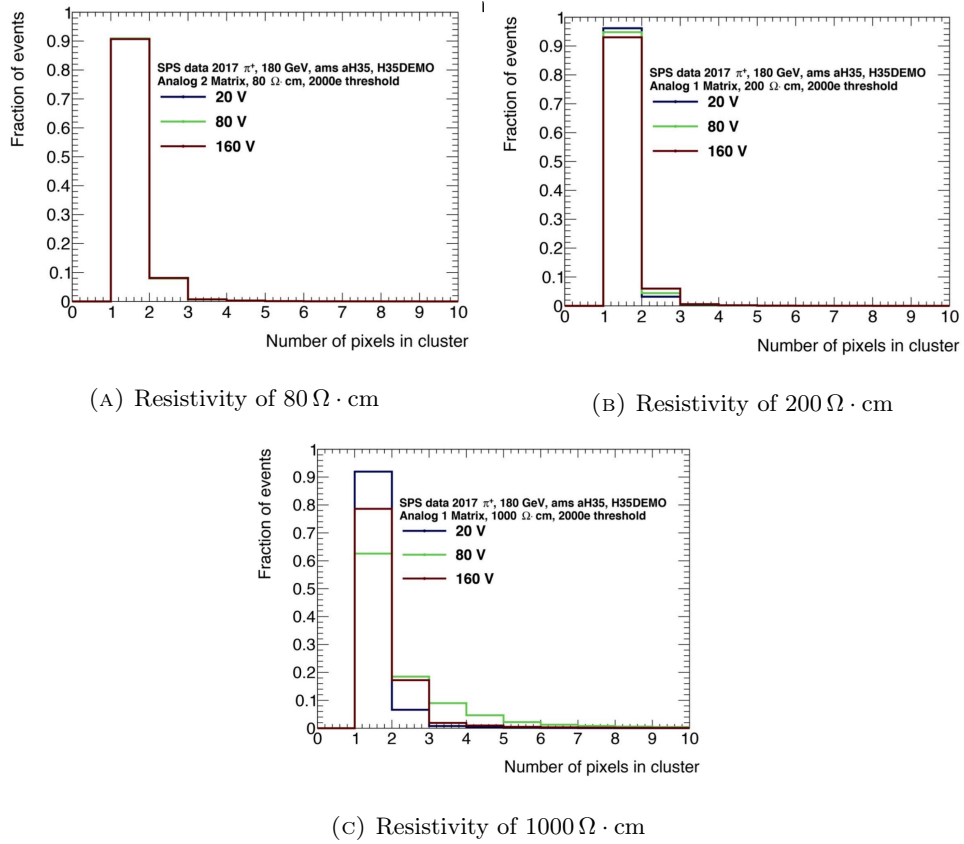


FIGURE 5.33: Cluster size distribution at different voltages for different resistivities [246].

The efficiency map and the efficiency as a function of the bias voltage are shown in Figure 5.34 for sub-matrix 2 of the Analogue1 matrix. The results for other sub-matrices are similar and hence Figure 5.34 is representative of the other measurements, however full results are documented in Ref. [246]. The consistent efficiency results across the geometry of the sensor shown in Figure 5.34(a) suggest that the capacitive coupling between the sensor and the FE-I4 is uniform, and hence the gluing between the sensor and the FE-I4 is homogeneous. The efficiency map depicts a single defective pixel. The decrease in efficiency in the furthest right column is caused by the sharing of the generated charge with the neighbouring matrix.

As expected, the efficiency distribution in Figure 5.34(b) shows the efficiency of the samples varies with the resistivity. Since the depletion depth is proportional to the resistivity and the bias voltage, a lower bias voltage is required to achieve the same depletion depth for a given

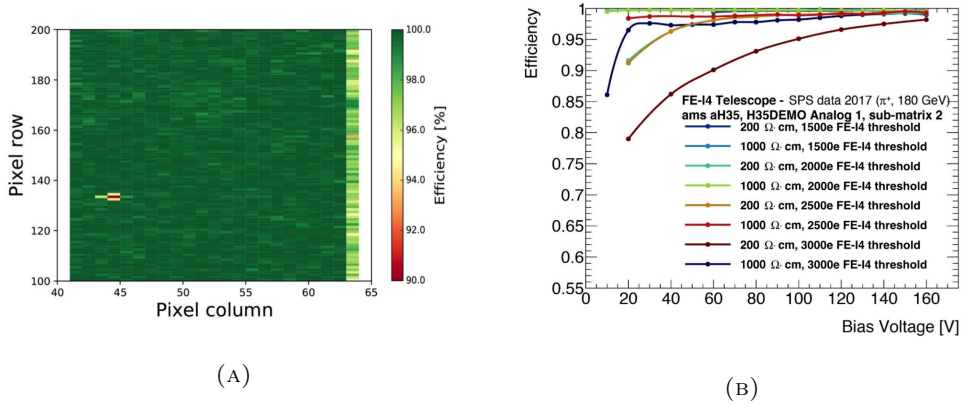


FIGURE 5.34: A) Efficiency map for the Analogue1 matrix. The decrease in efficiency of the last column is due to the proximity with the pixels of the neighbouring matrices, which can collect some of the charge at the edge of the matrix due to charge sharing. A single defective pixel is also present in the matrix. B) Bias scan for different resistivities and thresholds for sub-matrix 2 of the Analogue1 matrix [246].

increase in resistivity. All samples tested show an efficiency of 99%, confirming the previous results for the CCPD $v4$ devices.

Figure 5.35 presents the dependency of the timing resolution on the bias voltage and resistivity for the second high-gain matrix. No significant variation was observed for the other matrices, and so these results are representative. No clear dependence of the timing resolution on the bias voltage and resistivity is observed with most of the charge being collected in 2 BCs. Given that the collection time is proportional to the velocity of the charge carriers, which is expected to be dependent on the resistivity and bias voltage, it is a reasonable judgement that the timing resolution is instead mostly limited by the intrinsic *jitter* of the pre-amplifier and not the sensor signal amplitude or rise time. The jitter is a smearing effect on the timing resolution and is caused by various noise sources. In all cases, the timing distribution is less than 50 ns for bias voltages over 80 V.

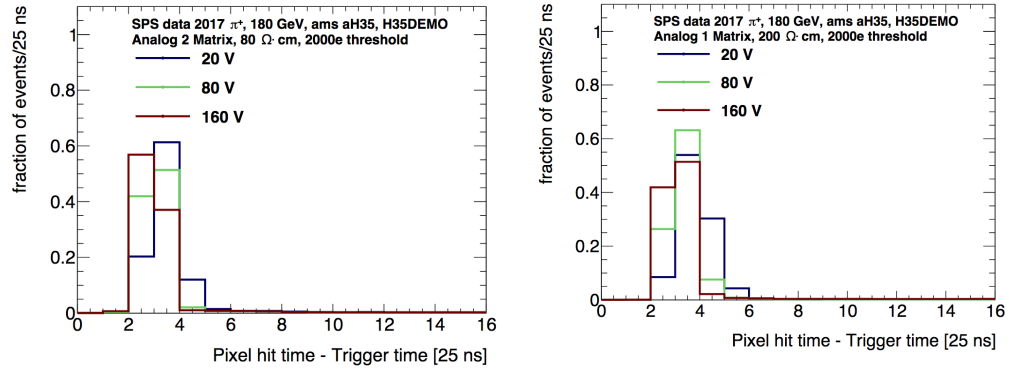
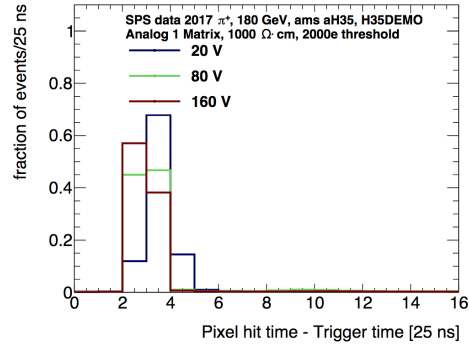
(A) Resistivity of 80 $\Omega \cdot \text{cm}$ (B) Resistivity of 200 $\Omega \cdot \text{cm}$ (c) Resistivity of 1000 $\Omega \cdot \text{cm}$

FIGURE 5.35: Timing distributions for the different resistivities [246].

5.10 Interpretation

Hybrid pixel detectors implementing the HV-CMOS technology were fabricated in both the 18 and 35 nm processes and were tested and characterised in extensive beam test campaigns to test their performance and suitability as an option for the outer-pixel layer of the ATLAS ITk upgrade. Hybrid CCPDv4 prototype sensors and capacitively coupled full size H35 Demonstrator prototypes were produced and tested as a precursor to the desirable monolithic HV-CMOS technology.

H18 CCPDv4 prototypes were glued to FE-I4 readout chips and irradiated in steps to mimic the expected fluences of the outer-pixel layer of ITk, where the maximum fluence received is $5 \cdot 10^{15} n_{eq}/cm^2$. The samples were irradiated with reactor neutrons and 18 MeV protons and tested in beam test measurements with high-energy pions at the SPS facility at CERN. Hit efficiencies of up to 99.7% at $1 \cdot 10^{15} n_{eq}/cm^2$ were observed. Compared to previous un-irradiated measurements, faster timing and less diffusion based charge collection was observed and was attributed to the acceptor removal effect, whereby the effective dopant concentration is reduced in the low resistivity ($10 \Omega \cdot cm$) silicon bulk. The characterisation of these prototypes shows impressive results that are comparable to the established planar pixel sensors. Following from these promising results, further prototypes were produced in various resistivities in the 35 nm process.

Extensive beam test measurements were performed using the H35 Demonstrator prototypes, a full size demonstrator sensor fabricated in the ams H35 HV-CMOS technology. These devices were produced in various resistivities (20, 80, 200 and $1000 \Omega \cdot cm$) in order to test the effect on the timing properties and efficiency. An efficiency greater than 99% is achievable for all prototypes. The advantage of higher resistivities is apparent in the bias voltage and FE-I4 threshold scan results. Higher resistivity substrates produce larger signals and better detection efficiencies at lower bias voltages. The results of the timing resolution measurements suggest little dependence on the substrate resistivity, indicating that the timing resolution is determined predominantly by the pre-amplifier itself.

These promising results represent an initial step towards the development of fully monolithic HV-CMOS pixel detectors. The small feature size of both of these prototypes allows for the pursuit of a fully monolithic design, which would revolutionise the instrumentation of large area tracking detectors.

Chapter 6

Conclusion

The contents of the presented thesis collate the active contribution of the author to the ATLAS collaboration from 2016 to 2019, during which time has signed over two-hundred ATLAS publications, whilst contributing directly to several published works:

- ATLAS Collaboration, *Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b -jets and missing transverse momentum*, [arXiv:1908.03122 \[hep-ex\]](#), to be published in Journal of High Energy Physics (2019).
- M. Kiehn et al., *Performance of CMOS pixel sensor prototypes in ams H35 and $aH18$ technology for the ATLAS ITk upgrade*, [Nucl. Instrum. Meth. A924 104-107 \(2019\)](#).
- M. Benoit et al., *Test beam measurement of ams H35 HV-CMOS capacitively coupled pixel sensor prototypes with high-resistivity substrate*, [Journal of Instrumentation, 13:12 P12009 \(2018\)](#).
- M. Benoit et al., *Results of the 2015 testbeam of a 180 nm AMS High-Voltage CMOS sensor prototype*, [Journal of Instrumentation, 11, 03 \(2016\)](#).

This thesis documents the analysis of a search for new physics phenomena and the research and development of silicon pixel detectors for the envisioned HL-LHC project.

The successful operation of the LHC has seen almost 140 fb^{-1} of pp collision data recorded by the ATLAS detector at an unprecedented centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. This wealth of data has allowed for significant advances in precision measurements of the SM, whilst also allowing for searches of new physics beyond that of our current comprehension.

The analysis presented targets a signature of pair produced bottom-squarks, where it is assumed that they are the only supersymmetric particle produced at the LHC and that they decay with a 100% branching ratio to a b -quark and $\tilde{\chi}_2^0$. The $\tilde{\chi}_2^0$ then subsequently decays with a 100% branching ratio to a Higgs boson and a $\tilde{\chi}_1^0$, the latter of which is stable and assumed to be the lightest supersymmetric particle (LSP). Shifting the focus from its initial discovery in 2012, the Higgs boson is exploited as a means of identifying new physics, with a dedicated algorithm attempting to identify and reconstruct the b -quarks from its subsequent decay. In the context of two simplified models, the designed event selections target final states considering no charged leptons, three or more b -tagged jets, and large missing transverse momentum. Bottom-squark searches performed prior to this analysis consider simpler decay chains and introduce fewer new particles, and hence the more complex decay chain allows to more effectively identify and reject events originating from SM processes. Whilst there are minimal discrepancies in the observed

and expected number of events, they are not statistically significant and are within the associated uncertainties. In the absence of a significant deviation from the number of expected SM events, limits on both generic models of new physics and on the signal models in question are derived. Exclusion limits at the 95% confidence level are placed on the visible cross-section and on the mass of the bottom-squark for a range of bottom-squark and neutralino masses. Bottom-squark masses up to 1.5 (1.3) TeV are excluded for $\tilde{\chi}_2^0$ masses up to 1100 (750) GeV in models with fixed $m(\tilde{\chi}_1^0) = 60$ GeV ($\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV). As the first search for such scenarios carried out by ATLAS in Run 2, these results represent a significant improvement upon the previous Run 1 result, considerably increasing the constraints on bottom-squark production by more than 350 GeV. These results are documented in a peer-reviewed paper to be published in the Journal of High Energy Physics [139].

Since the beginning of the supersymmetry research programme at the LHC experiments, a vast range of searches considering the simplest decay scenarios have been performed, however no evidence of supersymmetry has yet been observed. More complex searches were performed, using characteristic decay signatures of well motivated models in order to extend their sensitivity beyond that previously achieved by the initial, more general, searches. The complex searches provided improved exclusion power at the expense of excluding in a narrower region of phase space than the more general, simpler searches. Whilst the ATLAS detector is expected to record significantly more data with the scheduled LHC Run 3, it is not expected that this will significantly improve the sensitivity in these specific models, given the already abundant data. Supersymmetry searches would benefit from a statistical combination of the already existing results in order to more effectively cover the entire phase space. However, further development of improved reconstruction techniques could drastically improve the search sensitivity, where the presented analysis would benefit most significantly from improved high- p_T b -tagging capabilities. At high momentum, the B-hadrons are more boosted and hence their decay products are more collimated, leading to a higher hit density and track reconstruction ambiguities. As a result of the increased boost, it is also possible that the B-hadron decays beyond the first layer of the pixel detector, and hence the secondary vertex is in-between two pixel detection layers. A novel high- p_T b -tagging method has been proposed that is based, not on track reconstruction, but on the pixel hit multiplicity between the layers and is referred to as the *multiplicity-jump tagger* [255]. In a given cone around the jet-axis, the significant increase in pixel hits between layers is indicative of B-hadron decays.

Whilst the current pixel detector performs effectively, it is designed to tolerate a maximum fluence of $\sim 10^{15} n_{\text{eq}}/\text{cm}^2$, and hence the current radiation tolerance is inadequate for the envisioned HL-LHC phase. The HL-LHC project represents a unique challenge given the unprecedented levels of required radiation tolerance and timing resolution for the replacement inner detector, ITk. Whilst proven hybrid technologies will instrument the innermost layers of ITk, the outer layers are expected to receive a fluence of $1.5 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$, where this reduction in required radiation tolerance and event rate offers an opportunity to introduce and test a developing technology. The HV-CMOS technology is a novel pixel detector design that enables simpler production with a reduced material budget by integrating some or all of the readout electronics directly into one chip, with view to a fully monolithic implementation. The multi-layered structure allows the in-pixel electronics to be effectively shielded from the high bias voltage that significantly decreases the drift time of the collected charge. Small scale 180 nm feature-size hybrid HV-CMOS devices were irradiated and characterised in beam test measurements, achieving hit efficiencies of up to 99.7% at $1 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$. The characterisation of these prototypes shows impressive results that are comparable with the established planar pixel sensors. Extensive beam test measurements were subsequently performed using the H35 Demonstrator prototypes, a full size demonstrator sensor fabricated in 35 nm HV-CMOS technology. These devices were produced in various resistivities in order to test the effect on the timing properties and efficiency. An

efficiency greater than 99% is achievable for all prototypes. It was found that higher resistivity substrates produce larger signals and better detection efficiencies at lower bias voltages.

The very promising results from the characterisation of these hybrid devices represent an initial step towards the development of fully monolithic HV-CMOS pixel detectors and are published in two peer reviewed papers in the Journal of Instrumentation **13** (2018) P02011 [239] and **13**:12 P12009 (2018) [246]. The HV-CMOS technology allows for a significant reduction in production cost and material budget, whilst also proving highly efficient even at high radiation fluences. This technology, however, is still an on-going development, but will pose a promising candidate for the instrumentation of future tracking detectors.

Appendices

Appendix A

Additional Exclusion Limits

This appendix documents additional exclusion limits to those introduced in Section 4.10, presenting the best combined exclusion limits for the $m(\tilde{\chi}_1^0) = 60$ GeV and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV signal scenarios. Figures A.1 and A.2 additionally present the expected CL values at each signal mass scenario for the $m(\tilde{\chi}_1^0) = 60$ GeV and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenarios respectively. Whilst Figures A.3 and A.4 additionally present the upper limit on the signal cross-section for the $m(\tilde{\chi}_1^0) = 60$ GeV and $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV scenarios respectively.

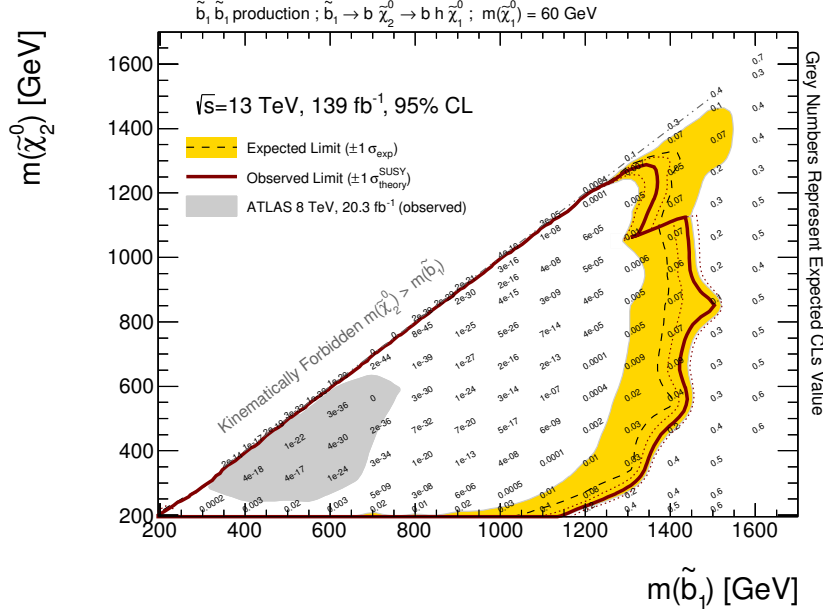


FIGURE A.1: Expected and observed best combined exclusion limits at 95% CL for the $m(\tilde{\chi}_1^0) = 60$ GeV simplified model in the $(m_{\tilde{b}_1}, m(\tilde{\chi}_2^0))$ plane. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model. Additionally, the expected CLs value for each signal model is presented.

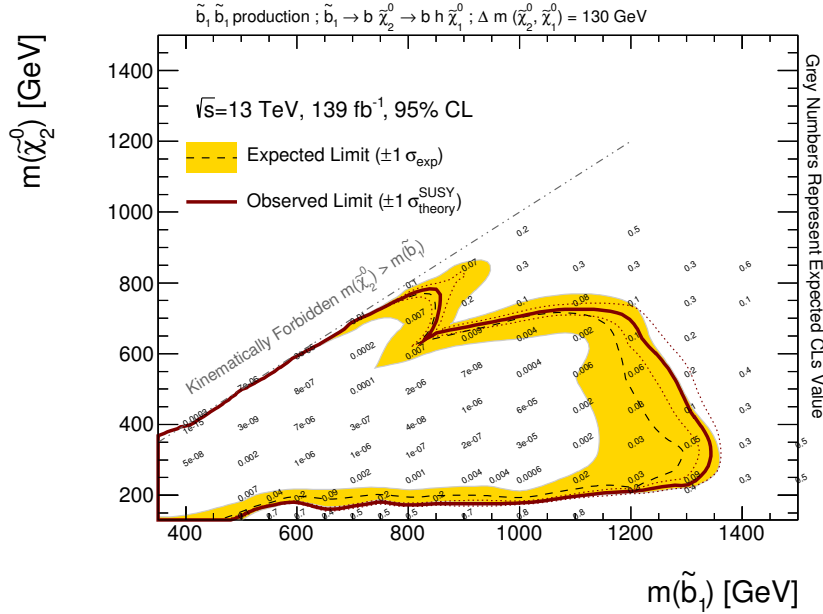


FIGURE A.2: Expected and observed best combined exclusion limits scenario at 95% CL for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV simplified model in the $(m_{\tilde{b}_1}, m(\tilde{\chi}_2^0))$ plane. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model. Additionally, the expected CLs value for each signal model is presented.

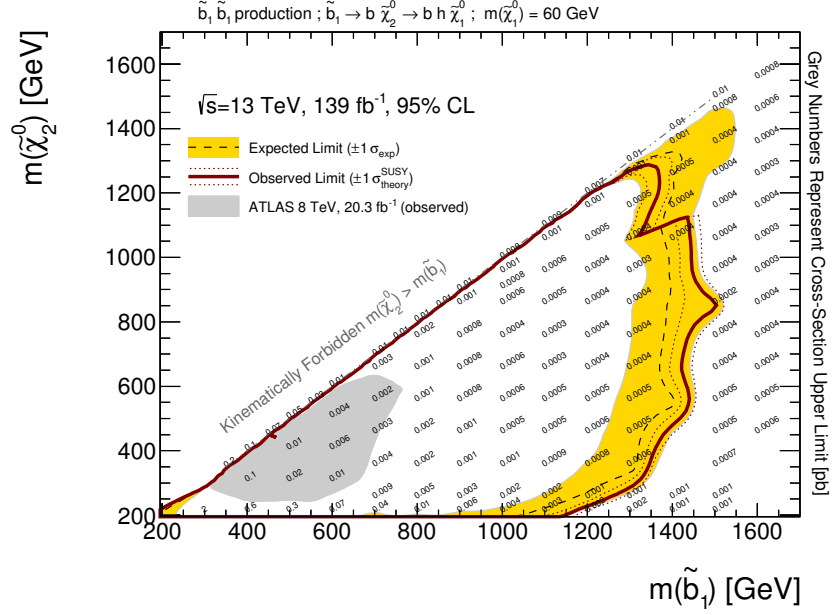


FIGURE A.3: Expected and observed best combined exclusion limits at 95% CL for the $m(\tilde{\chi}_1^0) = 60$ GeV simplified model in the $(m(\tilde{b}_1), m(\tilde{\chi}_2^0))$ plane. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model. Additionally, the upper limit on the signal cross-section for each signal model is presented.

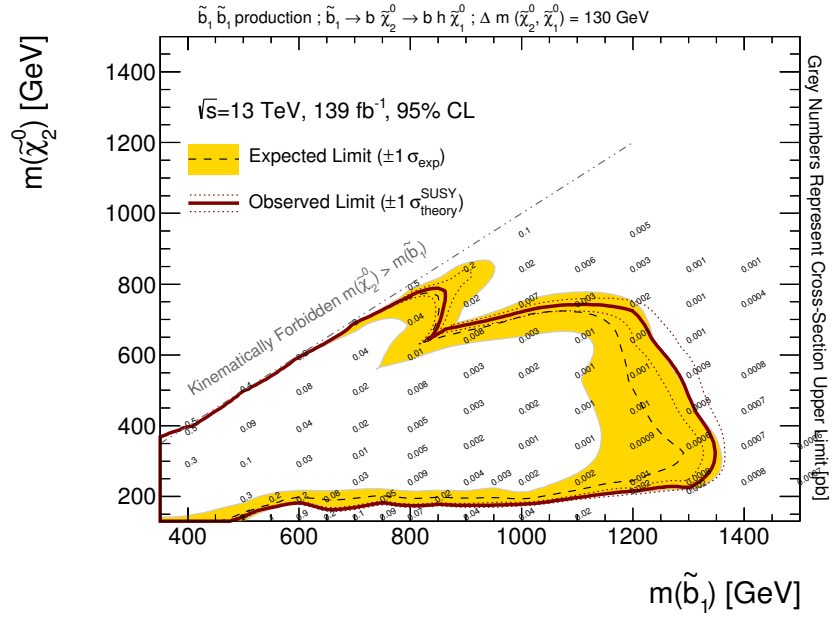


FIGURE A.4: Expected and observed best combined exclusion limits at 95% CL for the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV simplified model in the $(m(\tilde{b}_1), m(\tilde{\chi}_2^0))$ plane. The dashed blue line shows the 95% CL expected limit, while the shaded (yellow) bands around the expected limits show the impact of the statistical and systematic uncertainties. The red line shows the 95% CL observed limit, while the dotted lines around the observed limits show the impact of the theoretical uncertainties on the signal model. Additionally, the upper limit on the signal cross-section for each signal model is presented.

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Declaration of consent

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