

**3D detectors for the High Luminosity LHC, with a
feasibility study into the observation of ZZ
production in the $Z \rightarrow ee/\mu\mu$, $Z \rightarrow \tau\tau$ channel with
the ATLAS detector**

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Iain William Philip Haughton
School of Physics and Astronomy

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Iain William Philip Haughton – 2015

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Abstract

This thesis presents three bodies of work related to the ATLAS detector and physics measurements at the high luminosity frontier. The first investigates the use of 3D silicon detectors at the High Luminosity LHC. Several sensors are irradiated up to a fluence equal to that expected in the ATLAS pixel detector layers, and tests into their radiation tolerance performed. The second continues along a similar theme and pertains to the application of the 3D principle in an intrinsically more radiation tolerant material – diamond. The fabrication and testing of the first prototype 3D diamond detector for the purpose of particle tracking is described.

The final body of work moves away from the imperative technical work required with increased luminosity, to the potential gains in physics analysis. The feasibility of observing rare di-boson ZZ events in which one $Z \rightarrow ee/\mu\mu$ and the other $Z \rightarrow \tau\tau$, in data taken by the ATLAS detector is detailed. In addition to an increased luminosity, this analysis is likely to benefit from future upgrades to the pixel detector.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Finally, on a personal note, I would like to thank my parents Ann and Will Houghton, for their unwavering support and encouragement. To my siblings: Stephen, Peter and Andrew for their constant friendship.

To my parents.

*"C'mon down to the Particle Zoo,
where we smash things together, to make something new.*

Smash, bash, Particle Zoo, crash, smash, cos that's what we do.

*C'mon down to the Particle Zoo,
where we bash lions together, to make kangaroo.*

Smash, bash, Particle Zoo, crash, smash, to make kangaroo.

*C'mon down to the Particle Zoo,
where we crash giant panda, to make their bamboo.*

Smash, bash, Particle Zoo, crash, smash, to make their bamboo.

*C'mon down to the Particle Zoo,
if you bring along your friends, we'll smash them with you!*

Smash, bash, Particle Zoo, crash, smash, cos that's what we do!"

– I.W.P.H., Particle Zoo (a bit of thesis procrastination...)

Chapter 1

Introduction

1.1 The Standard Model

The ultimate aim of particle physics is to identify and explain the fundamental constituents (particles) and interactions (forces) that make-up the universe. To this end, our current ‘best guess’ takes the form of the Standard Model – a combination of free parameters determined from experimentation and predictions derived by quantum field theory [1]. It has become one of the most precise, well-tested and robust theories in physics. However, despite its success, the Standard Model has not been able to explain all phenomenon observed in Nature.

1.1.1 Particles of the Standard Model

The field of elementary particle physics began (arguably) with the discovery of the electron by J. J. Thompson in 1897. Although correctly assuming the electron to be an essential component of the atom, his ‘plum pudding’ model was discredited by Rutherford in 1911. Rutherford showed the atom’s mass to be concentrated at its centre in a nucleus, and in the case of hydrogen named this the ‘proton’. Subsequently a remarkably successful model of the hydrogen atom was devised by Bohr in 1914, consisting of a single electron orbiting a proton. Only after the discovery of the neutron by Chadwick in 1932 was an analogous description of the helium atom obtained, ending the so called ‘classical period’ of particle physics. At this time the answer to the question “what is everything made of?” would have simply been: electrons, protons and neutrons. However, several questions remained unanswered, in particular why the atomic nuclei did not simply break apart due to the repulsion of tightly confined positively charged protons. A new force was required.

Previously in 1905, Einstein had theorised the quantisation of the electromagnetic field to explain the photoelectric effect. The little packets of light proposed

by Planck in 1900 were in fact excitations of this field, and would later become known as ‘photons’. This idea became widely accepted after Compton’s experiment in 1923 showed the scattering of light from particles at rest. Eventually photons were incorporated into quantum field theory, and are now recognised to be the mediators, or gauge bosons, of the electromagnetic force. It is the exchange of photons between electrically charged particles that results in their attraction/repulsion.

In 1934, Yukawa proposed a new field analogous to the electromagnetic field, with corresponding gauge boson, to bind together protons and neutrons in the nucleus. The force had to be sufficiently strong to overcome electromagnetic repulsion, and was aptly named the ‘strong’ force. Since we do not experience its effect in everyday life, the strong force was chosen to be short-ranged, hence its gauge boson theorised to have a large mass. Yukawa named this unseen new particle the meson. The subsequent search for the meson led to the discovery of the pion (π) and muon (μ) by Bristol researchers in 1947. However, it would be some time before the true gauge boson of the strong force would be identified.

During this defining period of particle physics the first major achievement in the migration from non relativistic to relativistic quantum mechanics was made by Dirac. In 1927 he postulated the equation that bears his name, describing free electrons with energy given by the relativistic formula: $E^2 - p^2c^2 = m^2c^4$. However, at that time, his equation had a troubling feature: for every positive energy solution, there was a corresponding negative energy solution: $E = \pm \sqrt{p^2c^2 + m^2c^4}$. Given the natural tendency for every system is to evolve in the direction of lower energy, the electron should run away into increasingly negative states. Dirac’s solution was to define an infinite sea of electrons that would fill these negative states and prevent run-aways from occurring. The idea was met with skepticism among physicists and it wasn’t until 1940 that a more convincing answer was proposed by Stueckelberg and Feynman. Negative solutions of the Dirac equation could be re-expressed as positive solutions for a different particle - the anti electron, or positron. This particle had previously been discovered in 1930. The overriding implication was that all particles, not just the electron, would have a corresponding anti-particle with same mass but opposite charge. The anti-proton was discovered in 1955, and anti-neutron in the following year.

As a brief aside, in 1930, the problem of radioactive beta decay, in which a nucleus A transforms into a slightly lighter nucleus B with the emission of an electron, almost prompted Niels Bohr to abandon the law of conservation of energy. Fortunately Pauli proposed a more sober view, and the existence of a second (undetectable) particle, that carried away the missing energy – the neutrino. The neutrino’s anti-particle was finally discovered in 1955 with the observation of in-

verse beta decay.

With the existence of anti-particles and neutrinos, the collection of fundamental particles was beginning to look increasingly complicated. This was made even more so when a plethora of new particles known as baryons, and additional mesons known as kaons were discovered in the 1950s. All were produced on very short time scales, yet had long lifetimes in comparison, suggesting their production and decay were occurring via separate processes. In modern language these particles are produced via the ‘strong’ force (the same force holding the nucleus together) and decay via the ‘weak’ force (as responsible for beta decay). To explain this experimental evidence, Gell-Mann [2] and Nishijima [3] proposed a new property of a particle, ‘strangeness’. As in the case of charge, lepton number and baryon number, strangeness is conserved in any strong interaction, but (unlike the others) is not conserved in any weak interaction.

Strongly interacting particles could now be divided into two groups, baryons and mesons, in which each member was defined by its charge, mass and now strangeness. In 1961, Gell-Mann ordered these into what became known as the ‘Eightfold way’, analogous to the chemists’ periodic table, from which he predicted the existence of a previously unobserved particle the omega-minus [4]. Shortly after in 1964 the omega-minus was discovered [5]. In that same year, Gell-Mann and Zweig independently provided an explanation to why particles fitted nicely into the pattern of the Eightfold way. Particles were in fact composed of even more elemental constituents, that we now refer to as ‘quarks’. The quarks came in three types, or ‘flavours’: up, down and strange. Each flavour had fractional charge ($+\frac{2}{3}$, $-\frac{1}{3}$ and $-\frac{1}{3}$ respectively) and integer units of strangeness (0, 0, -1 respectively). These combined to make up the various baryons and mesons contained within the Eightfold way so far, following two simple composition rules: 1) every baryon is made of three quarks, and every anti-baryon of three anti-quarks; 2) every meson is made up of one quark and one anti-quark.

Despite its success in explaining the Eightfold way, by the late 1960s and 1970s the quark model was attracting some scepticism. Thus far no experiments had been able to produce or measure isolated quarks. With their unmistakable fingerprint of fractional charge, quarks should be very easy to recognise. Furthermore, at least one of the quarks should be very stable, since there is no lighter particle with fractional charge. In addition to this dilemma, the quark model also appeared to violate the Pauli exclusion principle. The Δ^{++} , for instance, is supposed to consist of three identical quarks in the same state. A solution was proposed by Greenberg in 1964 [6]. He proposed, in addition to their flavour, each quark possessed one of three colours (red, green or blue). Therefore the three u quarks contained within a Δ^{++} are no longer identical (one’s red, one’s green and one’s

blue). The colour hypothesis also introduces a simple characterisation of potential quark combinations, given that all physical, observable particles are colourless.¹ This explains why we don't see quarks anywhere other than bound up inside hadrons (colour confinement).

Confidence in the quark model grew further in 1974 with the discovery of the J/ψ meson. The new particle was extremely heavy and possessed an extraordinarily long lifetime (compared to the typical lifetime of other known particles). Both these factors pointed to existence of new physics, and eventually the discovery of a fourth quark, the charm quark ($J/\psi = c\bar{c}$). In the following years a series of new baryons and mesons containing charmed quarks were discovered, strengthening the concept of the quark model.

In 1975, the discovery of a new lepton, the tau (τ), hinted towards the existence of a further two quarks. These were required in order to maintain the symmetry between the number of quarks and leptons (of which there were now six: e , μ and τ plus their neutrinos). Fortunately it wasn't long until the discovery of yet another new heavy meson, the upsilon, in 1977. This implied the existence of a 5th quark, the bottom (b). The first b baryons and mesons were observed in the early 80s. Not surprisingly it was assumed the missing 6th quark, by now known as the top (t) quark, would soon be found. However, it wasn't until 1995 that it was eventually discovered by the experiments at the Tevatron collider at Fermilab and found to have a mass over 40 times heavier than the b quark.

Returning once again to beta decay, Fermi had first treated the process as a contact interaction, therefore requiring no intermediate bosons. Given the very short range of the weak force, this was a good first approximation. However, it was widely recognised that this approach would fail at high energies. Eventually the idea was reformulated to include a new particle to mediate the weak force. Only after the emergence of the electroweak theory (unification of the electromagnetic and weak forces) by Glashow, Weinberg and Salam, did a prediction of the vector boson masses become possible. There were in fact three: two charged ($W^\pm$) and one neutral (Z). These were first experimentally observed in 1983 by the UA1 and UA2 experiments at CERN ([7], [8], [7] and [9]), and had measured masses of:

$$M_W = (82.1 \pm 1.7) \text{ GeV}, \quad M_Z = (93.0 \pm 1.7) \text{ GeV}.$$

The mediator of the strong force is the gluon (g). Since gluons carry colour charge, it is not possible to directly detect them. However there is substantial indirect evidence that they exist.²

¹Here 'colourless' means either the total amount of each colour is zero or all three colours are present in equal amounts.

²In fact gluons carry both colour and anti-colour, an example being blue anti-green ($b\bar{g}$)

Particles of the Standard Model are given mass through interactions with the Higgs field. Excitations of this field produce the only spin-zero (scalar) particle in the Standard Model – the Higgs boson, H . The Higgs field and its associated particle were first proposed by Peter Higgs in 1964 [10]. Soon after, the Higgs mechanism was included into the formulation of the electroweak theory. Once the W and Z bosons had been discovered, the hunt was on for the last piece of the puzzle, the illusive Higgs boson. This finally bore fruit in July 2012, when the ATLAS and CMS experiments at the LHC announced they had observed a new particle consistent with a Standard Model Higgs boson. Its mass was around 125 GeV.

In summary, the three fundamental forces included in the Standard Model are explained by the continuous exchange of integer-spin ‘boson’ particles between half-spin ‘fermion’ particles.³ Fermions make up the building blocks of ordinary matter. They can be divided into two groups: those that interact via both the strong and electroweak forces – quarks, and those that interact via only the electroweak force – leptons. The gluon (g) is the boson responsible for the strong force and the photon (γ), W^+ , W^- and Z bosons for the electroweak force.

A list of all the fundamental particles contained within the Standard Model is given in Table 1.1.

Fermions			
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$
Leptons	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$
Bosons			
$\gamma, g, W^\pm, Z, H$			

Table 1.1: Summary of the fundamental particles contained within the Standard Model [1].

While undeniably a triumph of modern physics, the Standard Model is not the complete answer to understanding the universe. Unfortunately it has proven incompatible with the current theory of gravity (general relativity) [11]. However, since the gravitational force is 38 orders of magnitude weaker than the strong force, it only becomes important when making predictions at very high energies (matter densities). This energy scale is approximately 10^{20} times larger than that of experimental particle physics and therefore, for most purposes, gravity can be

³Note, bosons can also be exchanged between bosons (boson self couplings).

neglected.

The Standard Model also fails to describe two further observations at very large length scales, the first being the abundance of matter over anti-matter in the universe. Given the reasonable assumption that both were produced in equal quantities by ‘the Big Bang’ (as explained later), the Standard Model predicts an excess of matter over anti-matter shortly after the annihilation period (matter/anti-matter annihilation), but not to the extent seen in the universe, in fact, it under predicts by several orders of magnitude [12]. The second is the presence of ‘dark matter’ in the universe – a hypothetical form of matter required to explain several astronomical observations, including the rotation curves of galaxies and effects of gravitational lensing. However, unfortunately the Standard Model does not contain a particle that could be a legitimate candidate for dark matter. With the aim of solving some or all of these problems, many extensions to the Standard Model have been proposed, yet so far, none of them have been experimentally verified – physics beyond the Standard Model.

1.1.2 Symmetry and the Higgs Boson

The Standard Model is based on the mathematical principle of symmetry. Lorentz symmetry implies that the laws of physics look the same to any observer regardless of their frame of reference. Another important symmetry is gauge invariance. There are in fact different forms of gauge invariance in particle physics corresponding to different types of particle interaction. However, all maintain a common feature: the parameters of transformations are allowed to vary in space and time. For example, in Quantum Electro Dynamics (QED) – the theory describing the electromagnetic interaction – the theory is invariant under transformations of the form:

$$\psi(\mathbf{r}, t) \rightarrow \psi'(\mathbf{r}, t) = \exp \left[i \frac{q}{\hbar} \Lambda(\mathbf{r}, t) \right] \psi(\mathbf{r}, t) \quad (1.1)$$

where $\psi(\mathbf{r}, t)$ is the wave function of a particle of charge q and $\Lambda(\mathbf{r}, t)$ is an arbitrary real function. We could consider this transformation as the multiplication by a 1×1 unitary matrix $U = \exp[i\theta]$ with $\theta = \frac{q}{\hbar} \Lambda(\mathbf{r}, t)$. The group of all unitarity matrices is called U(1), and the corresponding symmetry U(1) gauge invariance. The same ideas can be applied to other forms of gauge invariance. For example, after including colour and the group SU(3) one can produce Quantum Chromo Dynamics (QCD) – the theory describing the strong interaction.

Gauge invariance implies that spin-1 bosons, like the γ and g , have zero mass, as shown in [13]. This is completely acceptable for QED and QCD since indeed both the γ and g do have zero mass. However, in trying to unify the electromag-

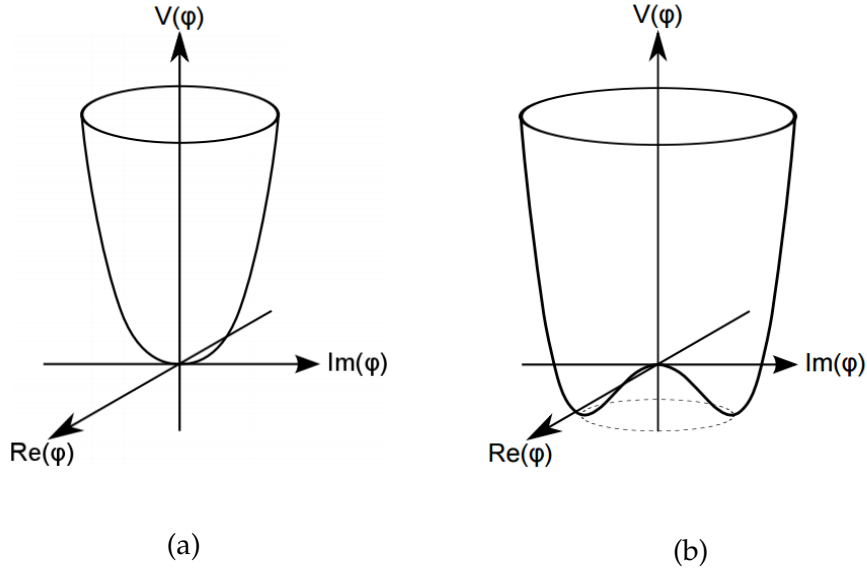


Figure 1.1: Two field potentials: a) in which spontaneous symmetry breaking does not occur, and b) in which spontaneous symmetry breaking does occur.

netic and weak forces, as in the case of the electroweak theory, clearly the $W^\pm$ and Z are not massless. This problem is overcome by incorporating the Higgs mechanism, marrying the concept of symmetry breaking with gauge invariance.

Interactions of the Higgs field with the gauge bosons are gauge invariant, however, in its ‘vacuum state’ (containing no particles of any kind), the behaviour of the Higgs field differs. Ordinarily for fields such as the electromagnetic field the vacuum state is equal to zero, whereas for the Higgs field there is a non-zero value of ϕ_0 that is not invariant under gauge transformation. As a result the $W^\pm$ and Z bosons are no longer required to have zero mass. This is known as ‘spontaneous symmetry breaking’, where the gauge invariance of the interaction remains exact, as opposed to the gauge invariance of the vacuum. Figure 1.1 shows two potentials, one in which there is a unique minimum and spontaneous symmetry breaking does not occur, and one in which there is no unique minimum and spontaneous symmetry breaking does occur. The Higgs potential takes the form of the latter.

In a similar manner to that of the W and Z bosons, masses of the fundamental fermions can be included into the Standard Model. Lepton doublets, as shown in Table 1.1, couple to the Higgs field via Yukawa interactions, giving the lepton masses.⁴ Analogous to the lepton doublets, quark doublets of the form:

⁴The Yukawa interaction is the interaction between a scalar and dirac field.

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix} \quad (1.2)$$

also interact with the Higgs field through Yukawa couplings, giving the quark masses. Here the down-type quarks are denoted with primes, these refer to the weak eigenstates rather than the mass eigenstates (i.e. the physical d, s, and b quarks). The principle of weak eigenstates was introduced by Cabbibo in order to explain the difference between the strength of the u – d and u – s weak vertices. The weak eigenstates relate to the mass eigenstates through the Cabbibo-Kobayashi-Maskawa (CKM) matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (1.3)$$

with real part matrix elements equal to [14]:

$$V_{CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix} \quad (1.4)$$

Charge-parity-symmetry or CP, states that in replacing a particle with its anti-particle (charge conjugation) and inverting the spatial coordinates (parity), the laws of physics remain the same. Both the strong and electromagnetic interactions have proven invariant under combined CP transformations. However, this symmetry has been shown to break, although only slightly, during certain types of weak decay. CP violation occurs in the Standard Model if a complex phase appears in the CKM matrix or the analogous PMNS matrix for neutrino mixing. This gives rise to processes occurring at different rates for particles and their anti-particles. When particles are produced via the strong force, we can assume both particles and their anti-particles are produced in equal number, yet their subsequent decay may occur at different rates. The first conclusive observation of direct CP violation came from neutral kaon decays in the 1960s.

The nature of the electroweak gauge group requires the existence of interaction vertices that involve three and four electroweak bosons, known as Trilinear Gauge Couplings (TGCs) and Quartic Gauge Couplings (QGCs) respectively [15]. However, due to certain symmetries and conservation laws not every combination of boson self couplings is allowed. In fact, the only allowed TGCs in the Stan-

Standard Model are: WWZ and $WW\gamma$, and QGCs: $WWWW$, $WWZZ$, $WWZ\gamma$ and $WW\gamma\gamma$. The precise measurement of boson self couplings provides important information about the nature of electroweak symmetry breaking. Deviations from that expected in the Standard Model would signal new physics, perhaps arising from loop corrections involving propagators of new particles, or anomalous particle couplings. Such phenomena are predicted by many models of physics beyond the Standard Model, with a notable example being Supersymmetry, proposing a fermionic partner for each boson in the Standard Model and a bosonic partner for each fermion. From Chapter 7 onwards an analysis that would potentially be sensitive to this and other such models is described.

By requiring gauge invariance under local gauge transformations, and including spontaneous symmetry breaking by way of the Higgs mechanism, we have arrived at the Standard Model of particle physics.

1.2 Units

In the field of particle physics it is common practice to set the values of $\hbar$ and c both equal to 1. Energies are expressed in terms of electron-volts, eV, with 1 eV approximately equal to 1.6×10^{-19} J. Hence in this system, the mass of the proton is equal to 0.94 GeV. Unless otherwise stated, these units, sometimes referred to as ‘natural units’ should be assumed throughout the rest of this thesis.

1.3 Particle colliders

Since energy and mass are equivalent, it is possible to study and discover new and unstable particles through high-energy particle interactions. The first experiments of this kind were performed using cosmic rays – streams of high energy particles with origin outside our solar system – and led to the observation of the positron along with several other notable discoveries [16]. Nowadays particles are accelerated using machines called accelerators, where the experimenter has the advantage of being able to control both the particle type and energy. Directing an accelerated particle beam on to a solid, liquid or gas, results in interactions between the projectile and the target material. Experiments of this type are known as ‘fixed-target’ experiments. Their main disadvantage is the amount of beam energy available for the production of new particles, otherwise known as the centre of mass energy $\sqrt{s}$. In a fixed target experiment this is given by:

$$\sqrt{s} = \left(m_b^2 c^4 + m_t^2 c^4 + 2m_t c^2 E_b \right)^{\frac{1}{2}} \quad (1.5)$$

where m_b and m_t are the mass of the beam and target particle respectively, and E_b the projectile's energy in the laboratory frame [13]. At higher projectile energies $\sqrt{s}$ only increases like $E_b^{\frac{1}{2}}$. This is a result of energy and momentum conservation, with the rest of the beam energy being imparted as kinetic energy to the target. Even so, in certain research areas, fixed target experiments are still contributing to important results: for example, the SHINE experiment at CERN (The European Organisation for Nuclear Research, Geneva), which studies the properties of hadrons [17].

The situation can be improved by accelerating both the projectile and target particle. In this case, if they have the same energy and mass, and are collided at zero crossing angle, then:

$$\sqrt{s} = 2E_b \quad (1.6)$$

and now the $\sqrt{s}$ is directly proportional to E_b [13]. Such experiments are known as 'colliders'. However, in comparison to fixed-target experiments, their interaction rate is lower, and experiments can only be made with stable beam particles, limiting the variety of interactions available.

Charged particles are accelerated by placing them in an electromagnetic (EM) field. Usually they are accelerated in bunches, to increase the probability of particle interactions when crossing the particle beams. Still, interactions are relatively uncommon: for example, in the Large Hadron Collider (LHC) at CERN, bunches typically contain $\sim 10^{11}$ protons, yet there are only approximately 20 interactions per bunch crossing [18].⁵ Accelerators can be split into two types: linear and cyclic. Linear accelerators accelerate particles in a straight line. The longest linear accelerator was at SLAC (Stanford Linear Accelerator Center), with a length of 3.2 km, it accelerated electrons/positrons up to an energy of 50 GeV [19]. The alternative is to accelerate particles over several cycles of a cyclic accelerator, known as a synchrotron. When travelling in a circular path, particles radiate energy inversely proportional to the fourth power of their mass, affecting the maximum beam energy [20]. This was the limiting factor for the Large Electron-Positron (LEP) collider at CERN [21]. To achieve higher beam energies, subsequent colliders such as the Tevatron [22], which operated at Fermilab, and the LHC, accelerate heavier hadrons that radiate less energy.

Since leptons are fundamental particles, when accelerating and colliding them, the amount of energy released in each collision is known to a high precision. The same is not true for composite particles like hadrons, which are formed from quarks. The quarks contained within the hadron have a distribution of momenta,

⁵As measured in 2012.

hence any interaction between them releases an unknown amount of energy. It can only be determined by measuring the energy and momentum of each particle emitted from the interaction, achieved using a precision particle detector. However, this is difficult when some particles, like neutrinos, do not interact with the detector. In colliding beams with zero crossing angle, the particle momentum in the plane traverse to the beam is assumed to be very small or zero for all interactions. Particle kinematics are therefore, in general, described in terms of energy and momentum transverse to the beam, E_T and p_T respectively.

1.4 The LHC

The largest circular collider currently in operation is the LHC. It has a circumference of 27 km and accelerates protons up to a record E_b of 6.5 TeV as of 2015 ($\sqrt{s}$ of 13 TeV). Two separate proton beams are accelerated in clockwise and anti-clockwise directions. Super-conducting dipole magnets direct the beams in a circular loop, and quadrupole magnets focus the beams at four interaction points around the circumference. Each interaction point is surrounded by a particle detector. These include: ATLAS (A Toroidal LHC Apparatus) [23], ALICE (A Large Ion Collider Experiment) [24], CMS (Compact Muon Solenoid) [25] and LHCb (LHC Beauty) [26]. Figure 1.2 shows the LHC complex layout, including the chain of machines required to accelerate the protons up to collision energies.

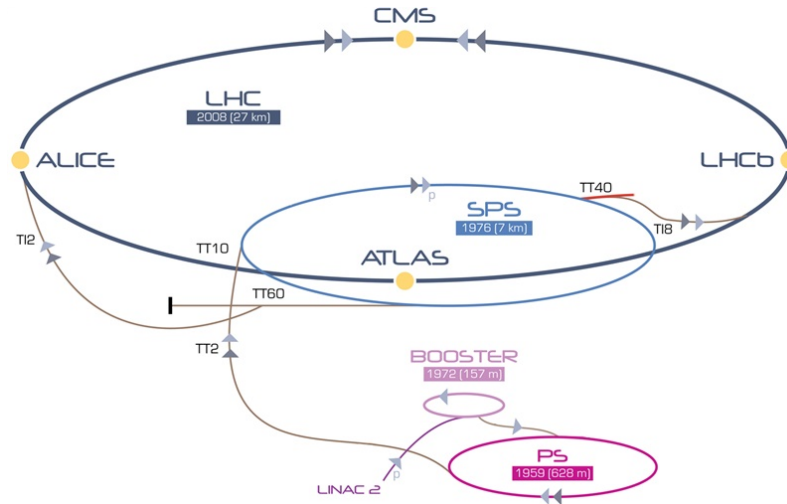


Figure 1.2: The LHC and its injection chain [27].

Protons are obtained through the stripping of electrons from hydrogen atoms in an electric field. They are placed into Linac 2 where they receive an initial acceleration up to 50 MeV. On reaching this energy, they are boosted by the Proton Synchrotron (PS) Booster and passed into the PS. Here, protons are accelerated further, up to an energy of 26 GeV. They are then transferred through Transfer

Tunnels (TT) 2 and 10 into the Super Proton Synchrotron (SPS) and accelerated further still, up to 450 GeV. Finally they are passed into the LHC. Those for the clockwise beam travel through TT60 and the Injector Tunnel (TI) TI2, and those for the anti-clockwise beam through TI8. In the LHC, protons are accelerated up to the final collision energy.⁶

In addition to its beam energy, a collider is characterised by its absolute luminosity, $\mathcal{L}$. This can most simply be expressed as the rate for a certain process, R , divided by the cross-section for that process, σ :

$$\mathcal{L} = \frac{R}{\sigma} \quad (1.7)$$

Luminosity is often given in terms an integrated luminosity, which is the integral of $\mathcal{L}$ over time. Figure 1.3 shows the cumulative integrated luminosity recorded in the ATLAS detector from the 1st of April – 1st of December 2012. Note, a total of 20.3 fb⁻¹ was determined to be good for physics analysis. This is referred to as the 2012 data set.

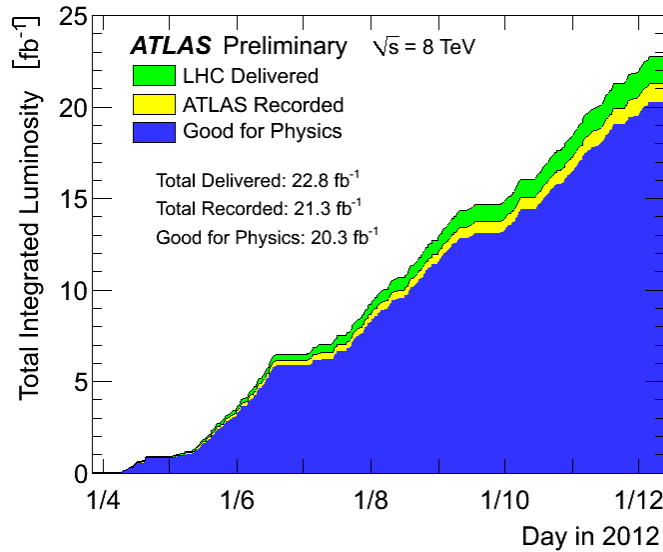


Figure 1.3: The cumulative integrated luminosity delivered by the LHC over 2012. The fraction recorded by the ATLAS detector is highlighted in yellow, and of that, good for physics analysis, in blue [28].

1.5 Design of the ATLAS detector

A cut-away of the ATLAS detector is shown in Figure 1.4. With a length of 46 m and diameter of 25 m, it has a cylindrical geometry, formed from a central barrel and two end-caps that surround the LHC beam. Protons collide at its centre and

⁶This was 3.5 TeV in 2010 and 2011, 4 TeV in 2012, and 6.5 TeV as of 2015.

particles are emitted outwards in all directions. Sub-detector layers determine each particle's type, energy and momentum. Solid state and wire chamber tracking detectors measure particle trajectory; EM calorimeters measure the energy of electromagnetically interacting particles; and hadronic calorimeters the energy of strongly interacting particles. In the outer part, muon spectrometers measure signals from muons. Two layers of magnets, a central solenoid and outer toroidal magnet, create magnetic fields that bend charged particles.

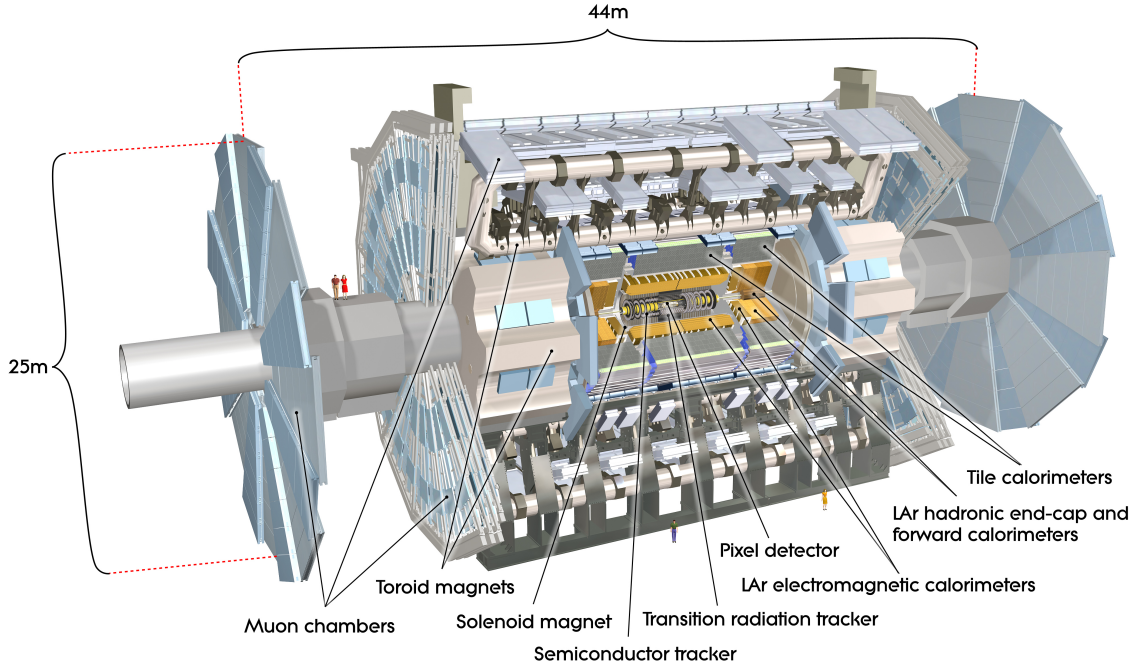


Figure 1.4: A cut-away of the ATLAS detector with the most significant sub-detectors labelled [29].

1.5.1 Coordinates

The LHC beam travels through the centre of the ATLAS detector and defines the z -axis of the coordinate system. Its origin is chosen to be the nominal interaction point of the proton-proton collisions. The x -axis is defined by the direction pointing from the origin to the centre of the LHC ring, and y -axis pointing from the origin upwards. Particle trajectories are described using spherical polar coordinates. The angle measured around the beam axis is denoted by ϕ , and the angle measured from the beam axis denoted by θ . Unlike the transverse plane, in which the net particle momentum is assumed to be zero, particles travelling in the longitudinal plane are likely to be Lorentz boosted. As such, it is preferable to use a 'pseudorapidity' η rather than θ , given by:

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (1.8)$$

The difference in η value of two massless particles, $\Delta\eta$, is then Lorentz invariant.

1.6 Thesis outline

Successive generations of colliders have seen a significant increase in both their centre of mass energy and luminosity. In doing so, each time, many technical challenges have had to be overcome. The reward has been the observation of increasingly rare and/or energetic processes. This thesis presents three bodies of work related to the next generation High Luminosity LHC. Chapters 4 and 5 introduce the first two, focussing on novel detector technologies designed to combat one of the biggest issues facing the inner-most layers of the ATLAS detector. The third is a feasibility study for observing a rare process in the ATLAS 2012 dataset, an analysis that will greatly benefit from a large increase in collected luminosity. First, the ATLAS inner-detector shall be described, detailing how it was in 2012, the upgrades made in 2013/2014 and those planned for the future; before a brief introduction into the basic theory of semiconductor detectors is given in Chapter 3. Finally, the ATLAS outer-detector shall be described in Chapter 6, and the feasibility study detailed in Chapters 7, 8 and 9.

Chapter 2

ATLAS part I

2.1 The inner-detector

The inner-detector (ID) is a collective term used to refer to the three inner-most tracking detectors: furthest from the beam-line the Transition Radiation Tracker (TRT), followed by the Semiconductor Tracker (SCT), and the pixel detector positioned closest to the beam-line. All three use the principle of ionisation within a medium to detect charged particles (c.f. Chapter 3), and each follows a similar blueprint with a central barrel and end-caps on either side. Figure 2.1 shows the ID layout of the central barrel. During operation it is immersed in a 2 T magnetic field generated by the central solenoid, in order to bend the path of charged particles.

2.1.1 The TRT

The outermost component of the ID is the TRT. It consists of 300 000 polyimide drift straw tubes, each with diameter 4 mm [30]. In the barrel region, these are arranged parallel to the beam, and in each end-cap, radially. The inner edge of each straw is coated with a layer of aluminium to act as a cathode, with a corresponding tungsten wire anode suspended at its centre. A Xe-based gas mixture is used as the ionising medium. A particle traversing the straw ionises gas atoms, leaving a trail of negative electrons and positive ions that are collected at the anode and cathode respectively. Under normal operating conditions, ionised electrons are collected within a collection time of ~ 50 ns and drift-distance accuracy of ~ 130 μ m [29]. The drift tubes are embedded in an array of polypropylene fibres, allowing for discrimination between electrons and charged pions: a relativistic particle entering a material with different dielectric constant (as at the drift tube – polypropylene interface) will radiate photons. The total energy radiated depends on the material properties, but also the Lorentz factor of the particle. Below par-

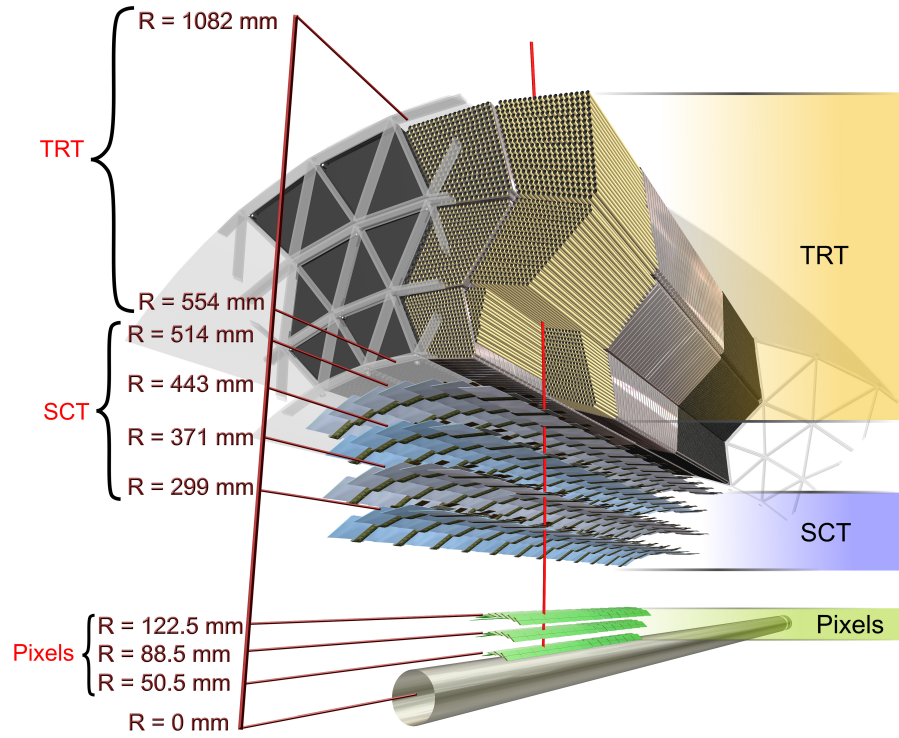
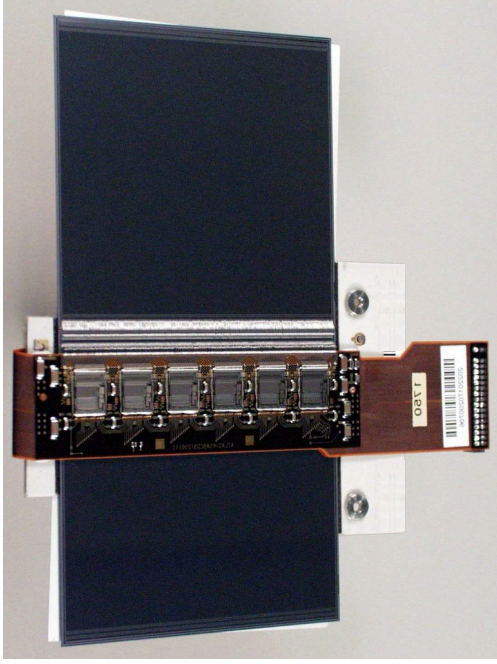
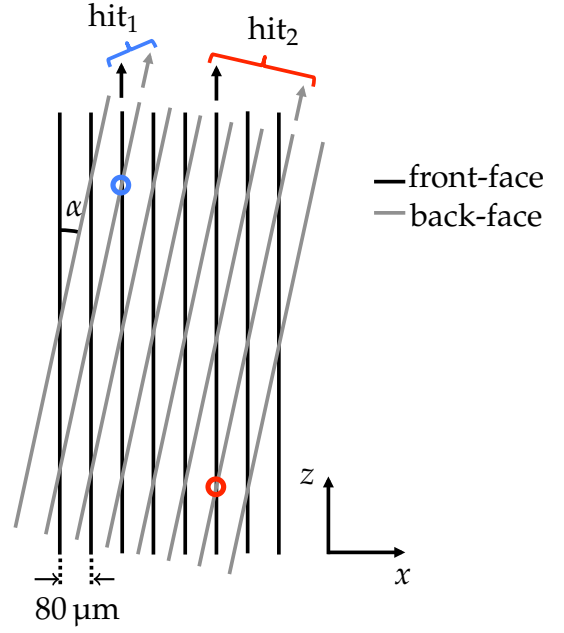


Figure 2.1: Diagram showing the central barrel lay-out of of the three sub-detectors contained within the ATLAS ID. The beam-pipe, through which the beam travels, is centred at $R = 0$ mm [29].



(a) SCT module [29].



(b) Strip configuration.

Figure 2.2: The SCT module design. a) an image of a barrel module. b) a schematic representation of the strip layout. The relative orientation of $\alpha = 40 \text{ mrad}$ allows for granularity in the z -direction with regards to locating hit_1 compared to hit_2 .

ticle energies of 100 GeV, in comparison to other charged particles, the electron (due to its low mass) will produce high pulse height hits in the drift tubes [31].

2.1.2 The SCT

Being positioned closer to the interaction point, a finer granularity is required in the SCT. To achieve this, planar silicon micro-strip modules are used [32]. Each module consists of four 770-strip sensors, two on either face, mounted back-to-back. The strips on the front face are orientated parallel to the beam, whilst those on the back face have a relative rotation of 40 mrad. Figure 2.2 shows an SCT module, and how the relative rotation allows for tracking information in the z -direction. A pitch width of $80 \mu\text{m}$ results in a granularity of $2000 \mu\text{m} \times 80 \mu\text{m}$, in the directions parallel and perpendicular to the beam respectively. The theory behind particle detection in silicon is described in Chapter 3.

2.1.3 The pixel detector

At the centre of the ID, and the very heart of ATLAS, is the pixel detector. It consists of three barrel layers, the closest of which is placed 50 mm from the beam-line (the ‘b-layer’), with three end-cap layers either side. As in the case of the SCT,

it uses planar silicon as a detecting medium, however, rather than strips, each module contains 47 232 pixels. The pixel size is $400\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$, corresponding to directions parallel and perpendicular to the beam. The granularity is such, that by extending a particle track back towards the interaction point, it can be determined whether the particle originated from the ‘primary vertex’ (approximately the interaction point of the two protons), or alternatively, to have originated from the decay of a ‘long-lived’ particle such as a τ -lepton, b- or c-hadron. ¹ In the latter case, the particle would originate from a ‘secondary vertex’ (the point at which the long lived particle decayed).

2.2 The insertable b-layer

During a long shut-down period from 2013 – 2014, the LHC was upgraded. Its machine luminosity and beam energy were increased, with the aim of producing more collisions of interest per bunch crossing, referred to as ‘pile-up’. This will have direct consequences for the ATLAS inner-detector, leading to a greater number and density of tracks, hence: a higher detector occupancy, reduced tracking efficiency, and increased radiation damage in detector modules, leading to premature failures (c.f. Chapter 3). Due to the b-layer’s proximity to the beam-line, it experiences the highest particle fluence (rate of particles intersecting per unit area). Over its extended lifetime, it was designed to withstand an integrated fluence of $5 \times 10^{14}\text{ n}_{\text{eq}}\text{ cm}^{-2}$ (c.f. Section 3.8). Levels that exceed this will result in module failure. In order to combat these technical issues and maintain the performance of the inner-detector, a supplementary layer of pixel detectors, closest to the beam-line, was inserted in 2013. Known as the Insertable B-Layer (IBL), it was positioned at a radius of 32 mm, in-between the current b-layer and a new beam-pipe. With increased granularity (pixel size of $250\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$) it reduces detector occupancy, and provides further redundancy against module failures. The additional layer of detectors also improves the accuracy and efficiency to which secondary vertices can be measured [33].

Being so close to the beam-line, the IBL is designed to survive a fluence approximately ten times that of the b-layer. Table 2.1 lists its operational requirements. In its final design, 75 % of the detecting area was chosen to be planar silicon, equivalent to, but more radiation tolerant than that in the pixel detector, and the remaining 25 % 3D silicon. The latter is a new technology, specifically designed to survive very high radiation fluencies (c.f. Chapter 4).

¹Here ‘long-lived’ refers to a lifetime of $\sim 10^{-12}\text{ s}$, which equates to a flight distance less than a few millimetres, falling short of the b-layer.

Requirement	Value
Fluence tolerance	$5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$
Hit efficiency	$>97\%$
Resolution (r - ϕ)	$<10 \mu\text{m}$
Maximum bias voltage	1000 V
Radiation thickness	$<500 \mu\text{m Si equiv.}$

Table 2.1: Operation requirements of detectors within the IBL [33].

2.3 The High Luminosity LHC

The High Luminosity LHC (HL-LHC) is a proposed major upgrade of the LHC after 2022 [34]. Its aim is to increase the current luminosity by a factor of 10, potentially collecting an integrated luminosity of 2500 fb^{-1} after 10 years of operation. In terms of physics, this will vastly increase measurement statistics. It will also enable the observation of very rare physics processes, that are currently out of the LHC’s sensitivity range. The increase in luminosity will predominantly come from the use of stronger quadrupole magnets, to squeeze and create higher density proton bunches at each interaction point. Proposed crab cavities will also enhance the bunch-bunch overlap [35]. The beam energy is likely to remain approximately as it is now, between 13 TeV to 14 TeV.

Concerning the ATLAS ID, the main challenge will be the vast increase in pileup, from 20 to 100 primary vertices per bunch crossing. Consequently, particle tracking will become very difficult. To have any chance of succeeding, a fast, high granularity, reliable ID, with layers close to the beam-pipe will be essential. Simulations have shown the current ID’s TRT, SCT and pixel detector layout to be inadequate [34]. So for the HL-LHC the ATLAS ID will be completely redesigned.

Figure 2.3 maps the cumulative radiation fluence expected in the HL-LHC at various distances from the interaction point. The inner-most layer will likely be positioned at a radius of $\sim 35 \text{ mm}$, and would therefore need to work adequately after receiving a fluence of $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Conventional planar silicon detectors would not survive this fluence, and likely fail within their operational lifetime. Hence it is necessary to find an alternative technology. With 3D silicon having been included in the IBL, it is a potential candidate. Another is ultra-thin planar silicon detectors, which, though not as advanced in terms of development, show great promise [36]. Then there is the possibility of migrating to new materials such as diamond, which are intrinsically more radiation tolerant than silicon (c.f. Chapter 5).

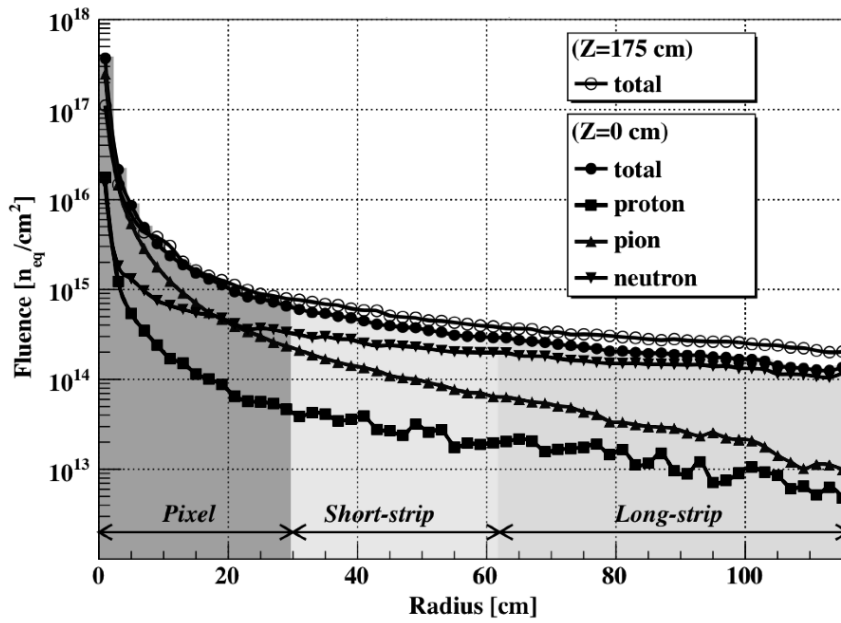


Figure 2.3: Expected fluencies in the ATLAS ID at the HL-LHC for an integrated luminosity of 3000 fb^{-1} . The fluence is mapped at two positions along the z -axis. The pixel detector is positioned closest to the interaction point, with higher granularity detectors placed further out [34].

Chapter 3

Semiconductor theory

3.1 Introduction

This chapter is intended to give a brief introduction into the basic theory of semiconductor materials and their use in particle detection. A more rigorous description of the topic can be found in [37], [38] and [39].

3.2 Elemental semiconductors

There are three elemental semiconductors commonly used for particle detection, including: carbon (in diamond form), silicon and germanium. The reasons why they, in particular, are good at detecting energetic particles, can be explained by the following. All three belong to Group IV in the periodic table with four electrons in their outer-most shell. A series of covalent bonds between these and those in neighbouring atoms, result in a highly ordered atomic lattice. Electrons contained within the lattice interact with its periodic potential and separate into a series of allowed energy levels dictated by the Pauli exclusion principle [40]. The lower of these are occupied by valence electrons locked in to the lattice and are known collectively as the valence band. Above this is the conduction band, containing free electrons that can contribute to the electrical conductivity of the material. In-between the two is a region of forbidden energy levels, known as the band-gap.

Electrons can be excited from the valence band into the conduction band when given an energy greater than the band-gap energy (E_g).¹ The excited electron leaves a mobile void in the valence band, or ‘hole’, that acts as a free electron with opposite charge but higher effective mass and lower mobility. The production of an electron-hole ($e-h$) pair allows both the valence and conduction bands to

¹In general this is approximately twice E_g plus 1.5 eV [37]

conduct. Table 3.1 lists each semiconductor along with its band-gap energy and energy required to produce an e - h pair.

Semiconductor	E_g (eV)	e - h (eV)
Diamond	5.5	13
Silicon	1.1	3.6
Germanium	0.7	2.9

Table 3.1: List of elemental semiconductors with their associated E_g and energy required to produce an e - h pair. [37]

The total number of e - h pairs, N_{e-h} present in a semiconductor is dependent on the band gap and the temperature, given by:

$$N_{e-h} \propto e^{-\frac{E_g}{2k_b T}} \quad (3.1)$$

where k_b is the Boltzmann constant and T the temperature. As such, at absolute zero there are approximately no e - h pairs and all semiconductors are essentially insulators. However, with increased temperature more-and-more electrons are excited into the conduction band and the material becomes conductive. Due to diamonds relatively large band-gap, even at room temperature (~ 300 K) it remains an insulator. The same is not true for silicon and germanium, which both become conductive at temperatures lower than room temperature [41].

3.3 The p-n junction

It is possible to alter the properties of a pure (intrinsic) semiconductor by adding small amounts of impurities, known as doping. Doping with group V elements (donors) leads to four covalent bonds and an additional free electron. This type of doped material is called n-type. Whereas doping with group III elements (acceptors) leads to three covalent bonds and an additional electron-void or hole, and is known as p-type. Figure 3.1 compares the energy band structure for intrinsic, n- and p-type semiconductors.

A p-n junction is formed when n- and p-type materials are brought into contact [42]. Figure 3.2 shows the resulting band structure. Initially electrons diffuse from n to p, leaving behind positive donor atoms; and holes from p to n, leaving behind negative acceptor atoms. The abandoned donor/acceptor atoms form a region of immobile space charge surrounding the junction. Eventually this produces a sufficient electric field to inhibit any further flow of carriers.

In the space charge region very few free charge carriers are present, hence it is known as the depletion layer. If an electric field is applied that aids the

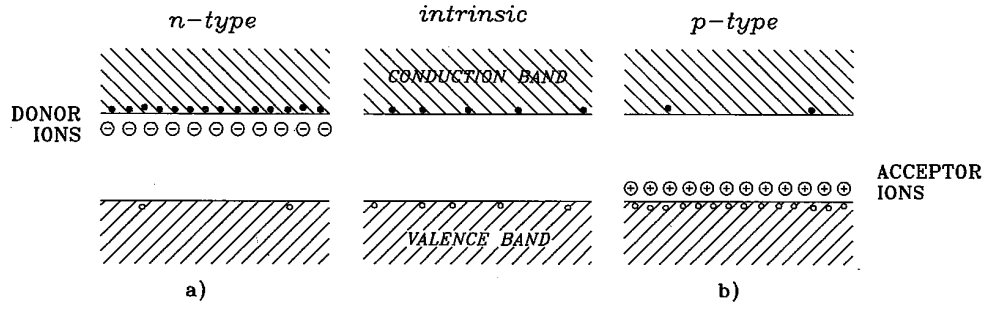


Figure 3.1: Diagram comparing the band structure in a) n-type and b) p-type materials to that of intrinsic material. In a) there is an excess of electrons (filled circles) in the conduction band, whereas in b) there is an excess of holes (hollow circles) in the valence band, allowing both bands to conduct [39].

movement of electrons/holes (reverse bias) the depletion layer will increase. At a critical potential, the whole sample becomes depleted, and essentially no carriers remain.

3.4 Particle detection

The energy loss, per unit distance, by a charged particle traversing a material is well-described by the Bethe-Bloch equation, and for a given material is only dependent on the particle's charge, mass and momentum [43]. Its energy is lost via 'ionisation'. Above a given momentum threshold, the energy loss reaches a minimum independently of the medium. Particles of this type are called Minimal Ionising Particles (MIPs), they lose only a fraction of their energy, depositing it uniformly along the particle track. When traversing a depleted p-n junction, this energy creates $e-h$ pairs that separate and move in the electric field. The number of $e-h$ pairs produced is proportional to the total energy lost by the particle in the material. This being so, the operation of a p-n junction as a particle detector relies on its ability to collect ionised charge. With the absence of any free carriers in the depletion region, electrons and holes can drift freely in the electric field with little risk of recombination, inducing a current. In addition to providing the electric field, electrodes placed either side of the depletion layer allow for any induced current to be collected as a signal, thereby forming a particle detector. Since intrinsic diamond is essentially devoid of free carriers at room temperature, unlike silicon and germanium, it can be turned into a particle detector directly, without any need of doping or the fabrication of a p-n junction [44].

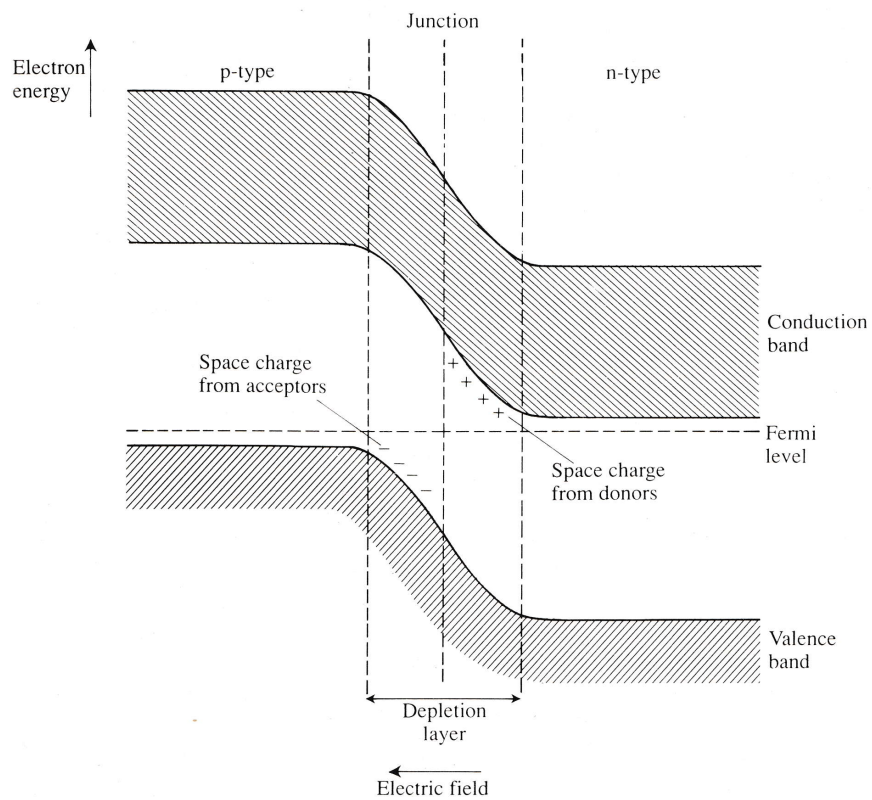


Figure 3.2: Diagram showing the change in band structure at the n- and p-type material interface. Immobile space charge forms an electric field that clears a depletion region of any free charge carriers [38].

3.5 Charge signal

The instantaneous current induced by the movement of a charge q with velocity v in a detector is given by the Shockley-Ramo theorem:

$$i = E_w q v \quad (3.2)$$

where E_w is the weighting field [45]. The induced current is measured as a charge signal, Q_s , and can be derived directly from Equation 3.2:

$$\begin{aligned} \frac{dQ_s}{dt} &= E_w q \frac{dx}{dt} \\ dQ_s &= E_w q dx \\ Q_s &= \int E_w q dx \end{aligned} \quad (3.3)$$

It is important to note the difference between the weighting and electric fields. The latter determines the charge's trajectory and velocity, whereas the weighting field determines how the charge's motion couples to a particular electrode, and is calculated by applying a unit potential to the measurement electrode whilst setting all others to zero. Only in a pad detector, where a single electrode is placed on either side of the depletion region, do the two fields have the same geometry.

3.6 Trapping

Plates of semiconductor material are grown using several well-developed techniques, as described here for silicon [46]. In essence all begin with a 'crystal' seed, from which epitaxial growth is nurtured. Although great care is taken, there are inevitably imperfections in the growth material, including dislocations in the atomic lattice and the presence of impurity atoms/molecules [47]. In general these are undesirable as they affect the movement of electrons and holes in the material. They insert additional energy levels into the band-gap that can act as 'generation' centres or 'deep level' traps. Figure 3.3 shows both these effects. In the first instance, electrons and holes are aided across the band-gap, generating a constant background current that adds to undesirable noise in the detector.² The second shows how electrons and holes maybe captured by a trap. Generally they will be released after some time T , however, if this is longer than the nominal collection time of the detector, then they will not contribute to the measured

²Noise can be described as the variation of ambient signal in a detector when there is no ionisation from a traversing particle. [48]

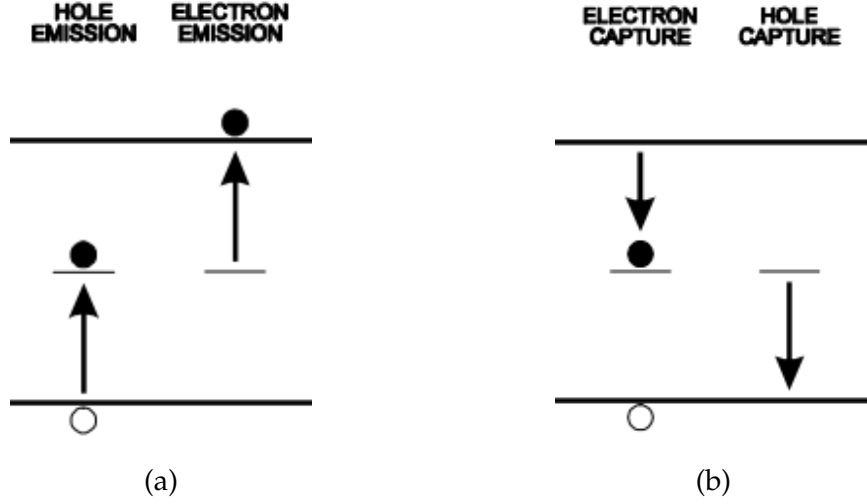


Figure 3.3: Schematic representation of a) current generation and b) charge trapping, after the insertion of intermediate energy levels into the band-gap as caused by imperfections in the atomic lattice. [39]

charge signal.³ The trapping effect is parametrised by assigning a mean lifetime, τ , to each carrier type, dependent on the number of imperfections present.

3.7 Charge signal with trapping

For simplicity we shall initially only consider one carrier type, the electron with mean lifetime, τ_e . In general, electrons and holes have different mean lifetimes, however, the basic principles, as described below, are the same.

If a packet of n_0 electrons, each with charge q , travels through a bulk material containing lattice imperfections, the number remaining after time t , $n(t)$, will be:

$$n(t) = n_0 e^{-t/\tau_e} \quad (3.4)$$

The motion of the packet is dependent on the electric field. Constituent electrons will travel in a direction parallel to the field with drift velocity, v_D , equal to:

$$v_D = \mu_e E \quad (3.5)$$

where μ_e is the electron mobility, and E the electric field [39].⁴ Therefore, the time required to travel a distance x is: $t = \frac{x}{v_D} = \frac{x}{\mu_e E}$, and Equation 3.4 can be written:

³At the LHC, the collection time can be as short as 10 ns.

⁴The same is also true for holes, however, there is a corresponding hole mobility, μ_h .

$$n(x) = n_0 e^{-x/\mu_e E \tau_e} = n_0 e^{-x/\lambda_e} \quad (3.6)$$

where λ_e is the mean free path of the electron and equal to $\mu_e E \tau_e$. With sufficient electric field strength, the drift velocity saturates, and λ_e becomes constant and independent of position. Assuming the simplest detector geometry: a pad detector with a single electrode on either side, the electric and weighting fields have the same form, with the weighting field equal to $\frac{1}{L}$, where L is the spacing in-between the electrodes. From Equation 3.3, the charge signal, Q_s , induced after travelling a distance x would then be:

$$\begin{aligned} Q_s &= \frac{q}{L} \int_0^x n_0 e^{-x/\lambda_e} dx. \\ &= n_0 q \frac{\lambda_e}{L} \left(1 - e^{-x/\lambda_e}\right) \end{aligned} \quad (3.7)$$

If we now consider the passage of a MIP, ionising electrons along its path. Assuming the electrons are distributed with $\rho_e(x)$, $\int_0^L \rho_e(x) dx = n_0$ across the detector's bulk, then we would expect a signal equal to:

$$\begin{aligned} Q_s &= \frac{q}{L} \int_0^L \rho_e(x) \int_0^{L-x} \frac{n(x')}{n_0} dx' dx \\ &= \frac{q}{L} \int_0^L \rho_e(x) \lambda_e \left(1 - e^{(x-L)/\lambda_e}\right) dx \end{aligned} \quad (3.8)$$

If the electrons are distributed evenly, then $\rho_e(x) = \frac{n_0}{L}$, and:

$$\begin{aligned} Q_s &= \frac{q}{L} \int_0^L \frac{n_0}{L} \lambda_e \left(1 - e^{(x-L)/\lambda_e}\right) dx \\ &= n_0 q \left(\frac{\lambda_e}{L} - \frac{\lambda_e^2}{L^2} + \frac{\lambda_e^2}{L^2} e^{-L/\lambda_e} \right) \end{aligned} \quad (3.9)$$

This is for one charge carrier, and only true when $\lambda_e \ll L$. To determine the total signal, we must sum contributions from both electrons and holes with corresponding mean free paths, λ_e and λ_h . This being so, usually the direct sum of λ_e and λ_h is used to give a quantitative description of a detector's material quality, and referred to as the Charge Collection Distance (CCD):

$$\text{CCD} = \lambda_e + \lambda_h \quad (3.10)$$

Clearly it is advantageous to have as larger CCD as possible, as this directly

affects the signal measured in a detector [49].

When a detector is placed in an intense stream of high-energy particles, over time the material is damaged, referred to as radiation damage. The mechanism behind this is described in the following section. One consequence is the gradual introduction of traps into the bulk. The additional traps reduce the carrier's mean lifetime, drift length and the detector's CCD. Consequently, one can see from Equation 3.9, that this affects the signal collected.

3.8 Radiation damage

When a detector is placed in a high-energy particle field, any incident particles have the potential to dislodge atoms from its atomic lattice, thereby inducing additional imperfections. A dislodged atom and the lattice void it left behind are referred to as a Frenkel pair [50]. Frenkel pairs have high mobility at room temperature and migrate around their local lattice site.⁵ After some time they will either recombine, or form 'point' defects with impurity/doping atoms resident in the semiconductor. Point defects contribute to additional energy levels in the band-gap and are a further source of charge traps. With continued exposure, over time more-and-more point defects will accumulate, gradually reducing the mean lifetime of carriers within the detector's bulk. This effect is referred to as 'radiation damage', and is one of the greatest challenges for the operation of particle detectors at the LHC.

A particle must impart an energy greater than the threshold displacement energy, E_d , in order to displace an atom from the lattice. Table 3.2 lists the approximate value of E_d for the three elemental semiconductors. Diamond has the highest value, and is therefore the most resilient to incident particles, or 'radiation tolerant'. Usually an energy greater than E_d is transferred, and the displaced atom itself goes on to knock out others from the lattice. Figure 3.4 shows the simulated path of a heavily recoiling knock-on atom having been hit by a 1 MeV neutron. It goes on to knock-out others from the lattice, initiating a chain of atomic collisions that eventually terminate when energies fall below the value of E_d . At the end of each atom's path, a cluster of point defects is formed.

In order to globally describe the radiation effect of many particle types incident on a semiconductor, it is assumed the damage caused is proportional to the total energy imparted to the primary knock-on atoms (the NIEL hypothesis). Therefore the damage produced by different high energy particles such as electrons, protons, alpha particles and gamma rays, can be directly correlated to neu-

⁵The mobility of a Frenkel pair is dependent on temperature.

tron damage results – usually scaled to the equivalent damage caused by 1 MeV neutrons [51]. Hence, although a detector may have been placed in a field of 800 MeV protons, the received particle fluence is stated in terms of the equivalent 1 MeV neutron fluence (n_{eq}). The expected reduction in carrier lifetime can then be correlated to this standardised fluence, and is given by:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \beta\Phi \quad (3.11)$$

where τ is the mean lifetime of the carrier, τ_0 the mean lifetime of the carrier before irradiation, Φ the n_{eq} fluence and β the damage coefficient [52]. Similarly, the increase in generation or ‘leakage’ current is given by:

$$I = I_0 + \alpha\Phi V \quad (3.12)$$

where I is the leakage current, I_0 the leakage current before irradiation, α the damage coefficient and V the detector volume [53].

Semiconductor	Approximate E_d (eV)
Diamond	35
Silicon	25
Germanium	20

Table 3.2: List of elemental semiconductors and their associated E_d [54], [55], [56] and [57].

One final and important affect of radiation damage is the change in effective doping of n- and p-type materials. Radiation-induced acceptor-like defects may act as supplementary acceptors, whilst at the same time donor atoms are removed. Therefore, over time n-type material may eventually mutate into p-type. This phenomenon is known as ‘type inversion’ and has previously been observed after high radiation fluencies. It affects the make up of the p-n junction and is in general an undesirable occurrence [58].

If a detector is removed from a radiation field, having received a sufficient dose, and left for some time at room temperature, point defects induced by radiation damage will begin to reorder. This involves forming more stable configurations with dopants/impurities in the lattice. The effect is known as ‘annealing’, implying that it reduces the amount of damage and its effectiveness. However, at the same time defects may become more effective (reverse annealing). The amount and type of annealing experienced is highly dependent on temperature and time [53].

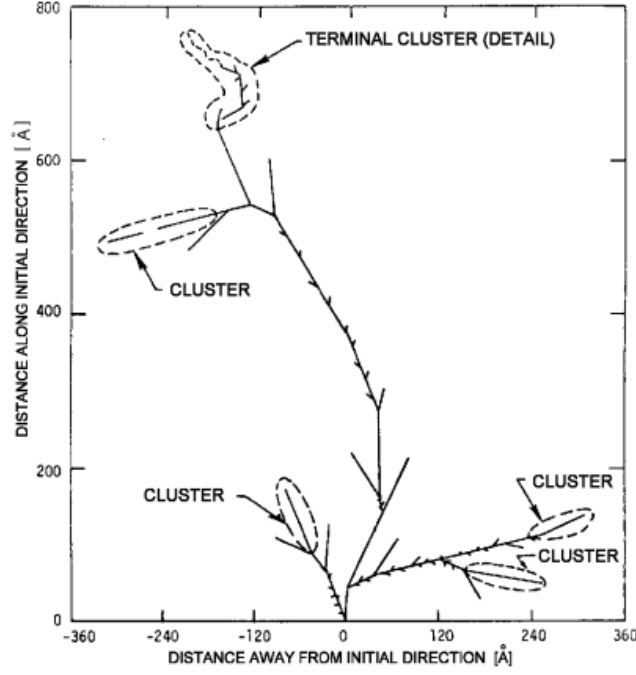


Figure 3.4: Spatial simulation of the atomic cascade and terminating point defect clusters caused by a 1 MeV neutron colliding with a primary knock-on atom in silicon. The atom was given an initial energy of 50 keV, equal to the average kinetic energy imparted by a 1 MeV neutron [53].

3.9 Signal efficiency

A good measure of a detector's performance degradation with exposure to radiation is the Signal Efficiency (SE). Defined as the ratio of maximum signal after radiation exposure to that before. If the detector is of good quality (large CCD) and has not previously been damaged, any effect of trapping before can be assumed negligible, $\lambda_e \gg L$ and $n(x) = n_0$ from Equation 3.6. In this case, the signal produced by a MIP, ionising a total of n_0 electrons evenly across the detector's bulk, would be approximately:

$$\begin{aligned} Q_s &= \frac{q}{L} \int_0^L \rho_e(x) \int_0^{L-x} 1 dx' dx \\ &= \frac{qn_0}{2} \end{aligned} \quad (3.13)$$

Calculated by taking the double integral of Equation 3.3. Hence the SE would be given by the ratio of Equation 3.9 to Equation 3.13, and equal to:

$$\frac{SE}{2} = \frac{\lambda_e}{L} - \frac{\lambda_e^2}{L^2} + \frac{\lambda_e^2}{L^2} e^{-L/\lambda_e} \quad (3.14)$$

With this parameterisation a total SE value of 1 can only be achieved when taking contributions from both electrons and holes into account. In reference [59] the effect of this equation has been simulated with varying CCD, from 50 μm to 300 μm , in which they assume a fixed relationship between λ_e and λ_h and deduce a simplified parametrisation for the SE, equal to:

$$\text{SE} = \frac{1}{1 + \frac{0.6L}{\lambda_e}} \quad (3.15)$$

Here the SE is dependent only on λ_e and the inter-electrode spacing L . As such, it can be directly related to the received particle fluence Φ , using relations 3.5, 3.11, the fact that $\lambda_e = \mu_e E \tau_e$, and assuming the value of τ_0 is negligible:

$$\text{SE} = \frac{1}{1 + \frac{0.6L\beta\Phi}{v_D}} \quad (3.16)$$

The following chapter compares this approximation to signal efficiency measurements from highly irradiated 3D silicon detectors. In this case, the above derivation neglects the highly non-uniform field distributions, even so the agreement is shown to be reasonable.

Chapter 4

3D silicon – radiation studies

4.1 Introduction

Three dimensional (3D) silicon detectors were first proposed in 1995, and successfully fabricated in 1997, offering, for the first time, an alternative to the conventional planar detector [60]. Both technologies use a plate of semiconductor material for their main body (bulk). However, in a planar geometry electrodes are placed at the top and bottom surfaces, forming an electric field perpendicular to the plate's surface. Whereas in a 3D detector, a three-dimensional array of columnar electrodes penetrate through the bulk, forming an electric field parallel to the plate's surface. Thus, charge ionised by a traversing particle is collected in alternate ways, as shown in Figure 4.1.

The key characteristic of a 3D geometry is the ability to reduce the inter-electrode spacing without reducing the detector thickness. If the inter-electrode spacing is chosen to be less than the bulk thickness, in comparison to an equivalent planar detector (equal in thickness), a 3D detector will have:

A greater radiation tolerance:

After heavy irradiation, the carrier's mean free path, λ , is assumed to be much smaller than the inter-electrode spacing, L . Thus, from Equation 3.14, the SE is approximately equal to λ/L , and with a bulk thickness of Δ , the signal collected is:

$$SE \times n_0 q \Delta \approx \frac{\lambda}{L} \times n_0 q \Delta \quad (4.1)$$

where n_0 is the total number of ionised carriers and q the carrier charge. For a planar geometry $\Delta = L$, and so the signal measured is equal to $n_0 q \lambda$. For a 3D geometry Δ and L are decoupled, hence, in comparison to the planar case, the signal can be increased by making $L < \Delta$.

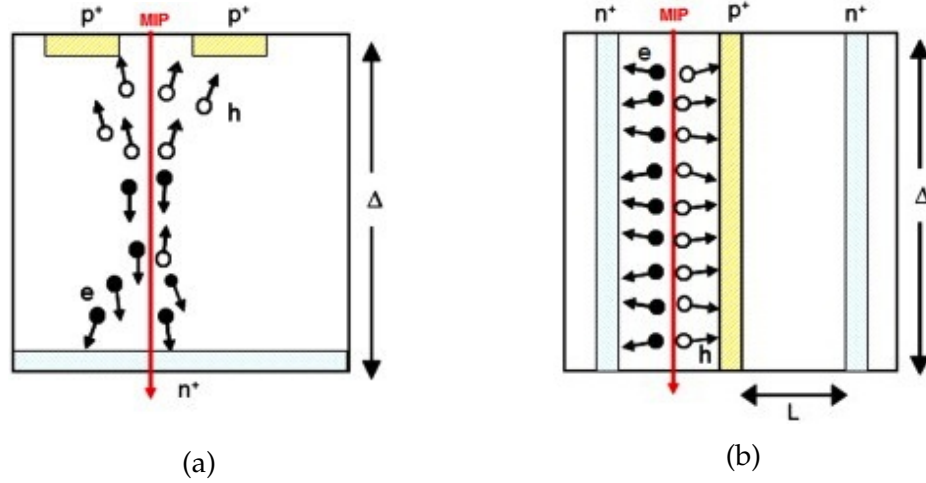


Figure 4.1: Schematic diagram comparing how charge ionised by a traversing MIP is collected in a) a planar geometry (strip detector) and b) a 3D geometry [61].

A reduced depletion voltage:

Since the depletion voltage is proportional to L^2 , a reduced bias voltage is required to fully deplete a 3D detector [62].

A reduced signal collection time:

Since the charge has to traverse a shorter distance in a 3D detector compared to a planar, assuming the carrier's drift velocity is saturated, full signal will be collected in a reduced amount of time.

Table 4.1 makes a comparison between typical values for 3D and planar detector parameters.

Geometry	3D	Planar
Inter-electrode spacing	50 μm	200 to 300 μm
Depletion voltage	<10V	30 to 100V
Signal collection time	$\sim 1\text{ns}$	Tens of ns

Table 4.1: Comparison of typical 3D and planar detector parameters. [61]

4.2 Fabrication

There are four main processing facilities where 3D silicon detectors are fabricated:

1. Centro Nacional de Microelectrónica (CNM) in Barcelona, Spain.

2. Fondazione Bruno Kessler (FBK) in Trento, Italy.
3. Stiftelsen for Industriell og TEknisk Forskning (SINTEF) in Oslo, Norway.
4. Stanford Nano-fabrication Facility (SNF), Stanford University, in California, USA.

All begin with 4 or 6 inch, float zone, $\langle 100 \rangle$ silicon substrates with typical resistivity of $\sim 20 \text{ k}\Omega \text{ cm}$. In general, these are p-doped, primarily for radiation hardness (c.f. Section 3.8). Electrodes are formed simultaneously using a Deep Reactive Ion Etching (DRIE) technique. First, an etch mask is patterned onto the substrate surface using standard photo-lithography. Then, fluorine ions are driven down on to the surface, etching away any exposed silicon, and hollowing out a column array. During each column's formation, any ions that do not react at the column's bottom, have the potential to etch away at its sides. To stop this, after several seconds of exposure, a passivation process coats the internal walls. The etch is then repeated. A continuous cycle of the etch and passivation process, results in an array of high-aspect ratio columns, that pass through the silicon bulk. Altogether, this is referred to as the 'Bosch' process [63]. In general, the hollow columns are filled with highly doped poly-silicon to form the n- or p-type electrodes. The charge collection efficiency within both n- and p-type electrodes has previously been measured to be $\sim 50\%$ compared to the detector bulk [64].

4.3 Full-3D and partial-3D

The process of etching, filling and doping n- and p-electrodes can be carried out from the same wafer side, or from opposing sides depending on doping type. In processing from the same side, a support wafer is required. However this allows for the formation of an 'active edge' – a trench electrode that borders the detector's active area, terminating the electric field lines of the most external electrode's row. In processing from alternate sides, there is no possibility of a support wafer, and hence an active edge cannot be fabricated. Instead a 'guard ring' structure is formed, increasing the amount of 'dead area' (non-active for particle detection) around the device. The advantage of processing from opposite sides is the ability to fabricate devices with electrodes that only go partially through the bulk. Furthermore, only one electrode type requires detailed surface patterning for read-out, with the other simply being shorted together on the opposite side. Devices fabricated with these alternate methods are referred to as full-3D and partial-3D detectors respectively, [63] and [65]. Of the 3D detectors contained

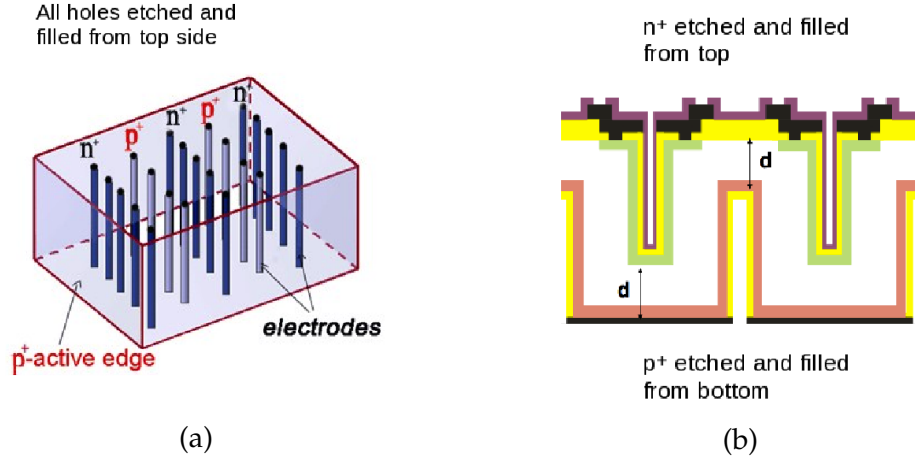


Figure 4.2: Comparison between a) a full-3D and b) a partial-3D detector. In b) there is a depth, d , of unprocessed bulk material at the end of each column, improving the overall charge collection efficiency in the column region [33].

within the IBL (c.f. Chapter 2), there is an approximate half-and-half split between full-3D and partial-3D technologies.

Figure 4.2 compares the cross-section of a full-3D and a partial-3D detector. In 4.2 a) the electrodes pass fully through the detector's bulk, with an n and p overlap throughout. In 4.2 b) the electrodes pass partially-through, only overlapping in the central region. In this case, there is an improved charge collection efficiency in the column region compared to a full-3D detector, due to the column not passing fully through the detector bulk.

4.3.1 Charge multiplication

After moderate radiation fluencies (greater than $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$), previous measurements on partial-3D detectors at bias voltages greater than 200 V have shown charge multiplication. In some cases this has resulted in a higher signal collection after irradiation, compared to that before [66]. This is believed to be a phenomenon only present in partial-3D detectors, due to very high electric fields present around the n- and p-column tips that induce carrier cascades. Simulations have shown that these fields only become sufficiently high after the insertion of deep level traps into the detector bulk, as caused by radiation damage. For a partial-3D detector of thickness $300 \mu\text{m}$, with n-column length of $160 \mu\text{m}$, p-column length of $190 \mu\text{m}$ and inter-electrode spacing of $56 \mu\text{m}$, after receiving $1 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$, Figure 4.3 shows the simulated electric field profile at different depths. At $140 \mu\text{m}$ and $190 \mu\text{m}$, around the n- and p-column tips respectively, there are large spikes in the field distribution. In comparison, at a depth of $150 \mu\text{m}$ where the columns overlap, as throughout a full-3D detector, the field distribution is comparatively uniform and no charge multiplication occurs.

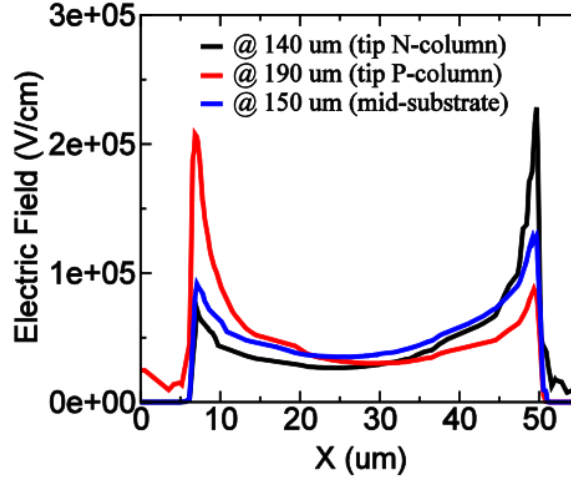


Figure 4.3: Electric field profiles in-between the p-column (at $x = 0 \mu\text{m}$) and n-column (at $x = 56 \mu\text{m}$), at depths of $140 \mu\text{m}$, $150 \mu\text{m}$ and $190 \mu\text{m}$ in a partial-3D detector [67].

4.4 3D silicon for the HL-LHC

Having been placed in the IBL, both full-3D and partial-3D detectors are potential candidates for the HL-LHC ATLAS pixel detector (c.f. Chapter 2). Nevertheless, their current radiation tolerance would need to be improved to survive the factor of ~ 10 increase in expected particle fluence. This could be achieved by using a smaller inter-electrode spacing. However, a reduced inter-electrode spacing leads to a higher electrode density, hence: increased detector capacitance, noise, and volume with reduced charge collection efficiency. Thus there is a fine balance between acceptable detector performance and enhanced radiation tolerance. Previous tests have measured the effect of various inter-electrode spacings on a 3D detector's signal and noise having received moderate radiation fluencies [68]. As a result, an inter-electrode spacing of $72 \mu\text{m}$ was chosen for the IBL. For the HL-LHC, it is likely a spacing in the region of $50 \mu\text{m}$ to $60 \mu\text{m}$ will be used.

Tests on partial-3D detectors, with an inter-electrode spacing of $56 \mu\text{m}$, have measured the signal degradation after a radiation fluence of $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ [69], [66] and [70]. As of yet, no comparable measurements have been performed on full-3D detectors. The remainder of this chapter shall detail the first equivalent measurement for a full-3D detector.

4.5 Full-3D test sensors

The full-3D test sensors were fabricated at SINTEF in Norway. They were front processed, with etching, filling and metallisation of all electrodes from the same

wafer side, the opposite having been bonded to a support wafer. Details on their fabrication are reported in [63]. Their main features include:

1. n^+ and p^+ column electrodes within a p-type bulk. Filled with poly-silicon, all electrodes go fully-through the bulk with a diameter of $\sim 10\ \mu\text{m}$.
2. Inter-electrode spacing of $56\ \mu\text{m}$ between electrodes of opposite type, as shown in the cross-section in Figure 4.5. A layer of p^+ (p-spray) below the surface isolates junction columns.¹
3. A p^+ trench electrode active edge.

The device layout is shown in Figure 4.4. Alternate rows of n and p electrodes form 510 quadratic cells, each with an n^+ electrode at its centre and a p^+ electrode in each of its four corners. The cell size is $50\ \mu\text{m} \times 100\ \mu\text{m}$. Cells are read-out using a strip metallisation, with all p-columns connected to a single bias pad, and all n-columns separated into 11 read-out pads. The sensor can be segmented by mechanically breaking the connections, as circled, in-between read-out pads. Segments S_1 , S_2 and S_3 connect to 5, 4 and 8 cells respectively; segments S_4 to S_9 and S_{11} each connect to one row (17 cells); and S_{10} to 22 rows. Sections 4.7.5 and 4.9 describe signal, current and capacitance measurements from segments S_3 , S_6 and S_9 , where their respective volumes are important. Segments S_6 and S_9 are equal in volume, whereas segment S_3 is 0.47 that of S_9 .

4.6 Sensor characterisation

The two most important parameters when operating a silicon detector, are its full depletion voltage, V_{FD} , and leakage current, I . The following sections describe experimental methods for determining each of these. A total of five test sensors were characterised in this way, referred to as A0, A1, B0, B1 and C0 throughout.

4.6.1 CV measurements

The capacitance voltage (CV) and $1/C^2$ measurements for each of the sensors are shown in Figure 4.6. In determining the crossing point of the two lines in Figure 4.6 b), it is possible to deduce an approximate value for V_{FD} . For all sensors this is measured to be $\sim 5\ \text{V}$. Operating at a bias voltage below V_{FD} results in the sensor

¹During fabrication, the silicon oxide layers become positively charged and attract electrons that have the potential to short n and p columns, resulting in a premature breakdown of the sensor. To prevent this, a layer of p-spray is inserted at the interface between the silicon oxide and p bulk. This p-spray has a higher doping than the p bulk and captures electrons, ensuring electrical isolation of the junction columns.

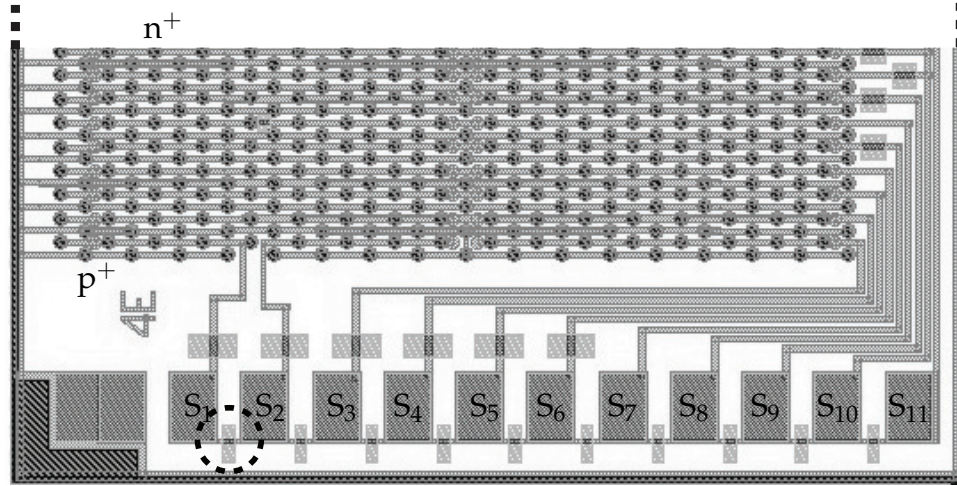


Figure 4.4: Sensor layout. All electrodes of the same type are connected together. Segments, labelled S_1 to S_{11} , may be separated by mechanically breaking the connections, as circled, in-between the read-out pads.

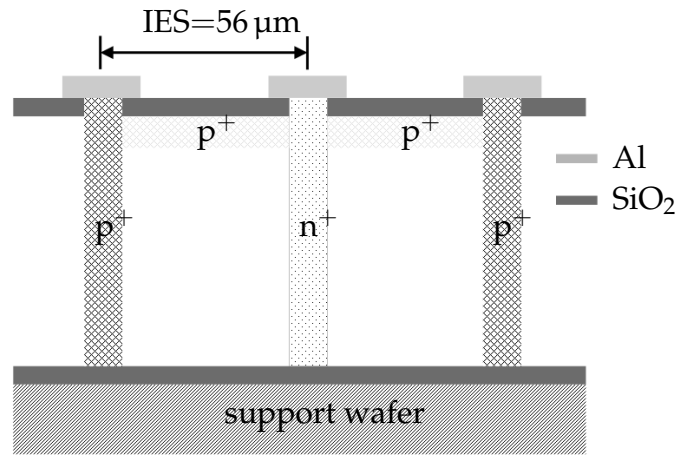


Figure 4.5: The cross-section of a test sensor. The n- and p-electrodes are separated by an inter-electrode spacing of $56\ \mu\text{m}$.

not being fully depleted, and therefore maximum signal not being collected. The measurements were performed using a *Boonton 7200* meter, which could measure a capacitance value with sensitivity of less than $1\ \text{pF}$.

4.6.2 IV measurements

The leakage current versus bias voltage (IV) curves for each of the sensors are shown in Figure 4.7. These were performed using a *Keithley 2410* source meter, which could measure a current with sensitivity of order nA . Above a certain voltage, an avalanche breakdown occurs and the the leakage current rises rapidly. Operating a sensor above this voltage has potential to cause lasting damage. The

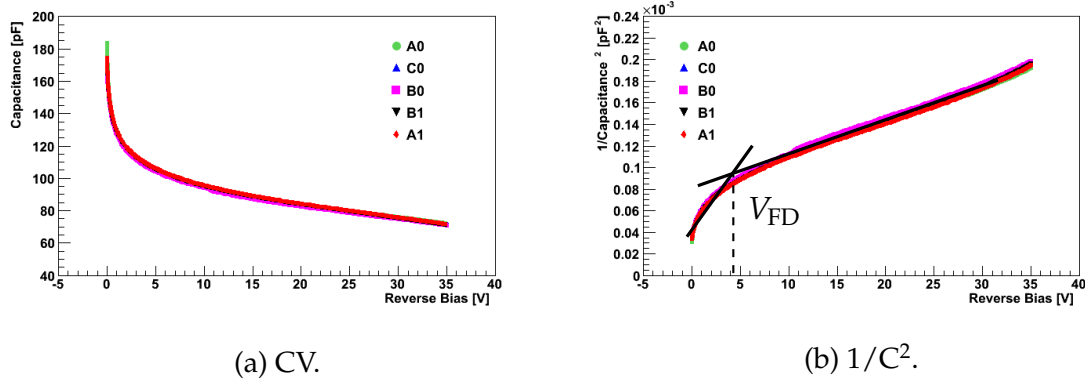


Figure 4.6: CV measurements for the five test sensors before irradiation. From b) it is possible to approximate the value of V_{FD} .

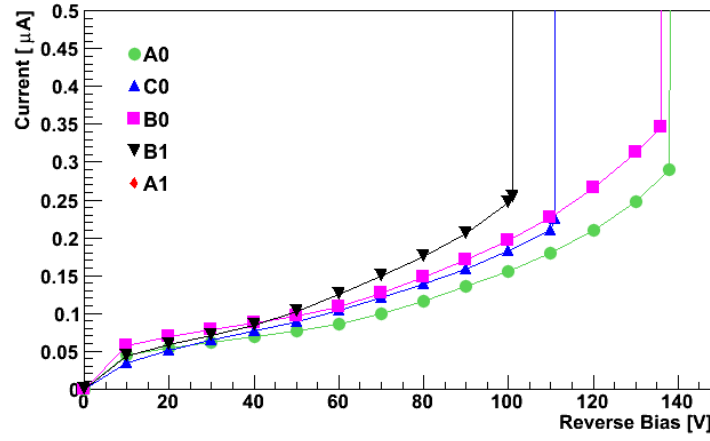


Figure 4.7: IV measurements for the five test sensors before irradiation.

earliest sensor breakdown was measured at ~ 100 V.

4.7 Signal measurement

To acquire signal measurements from each of the sensors, a laser set-up was constructed. It was based on a design described in [71] and [72]. The addition of a beam profiler allowed for accurate signal measurements from small areas of each sensor, as well as measurements of the reflected light intensity. The set-up was mounted in a probe station with surrounding faraday cage to reduce RF noise. This also enabled measurements to be made in a dark, light tight environment. A schematic diagram of the experimental set-up is shown in Figure 4.8. The following subsections describe each of its main components with reference to labels in Figure 4.8.

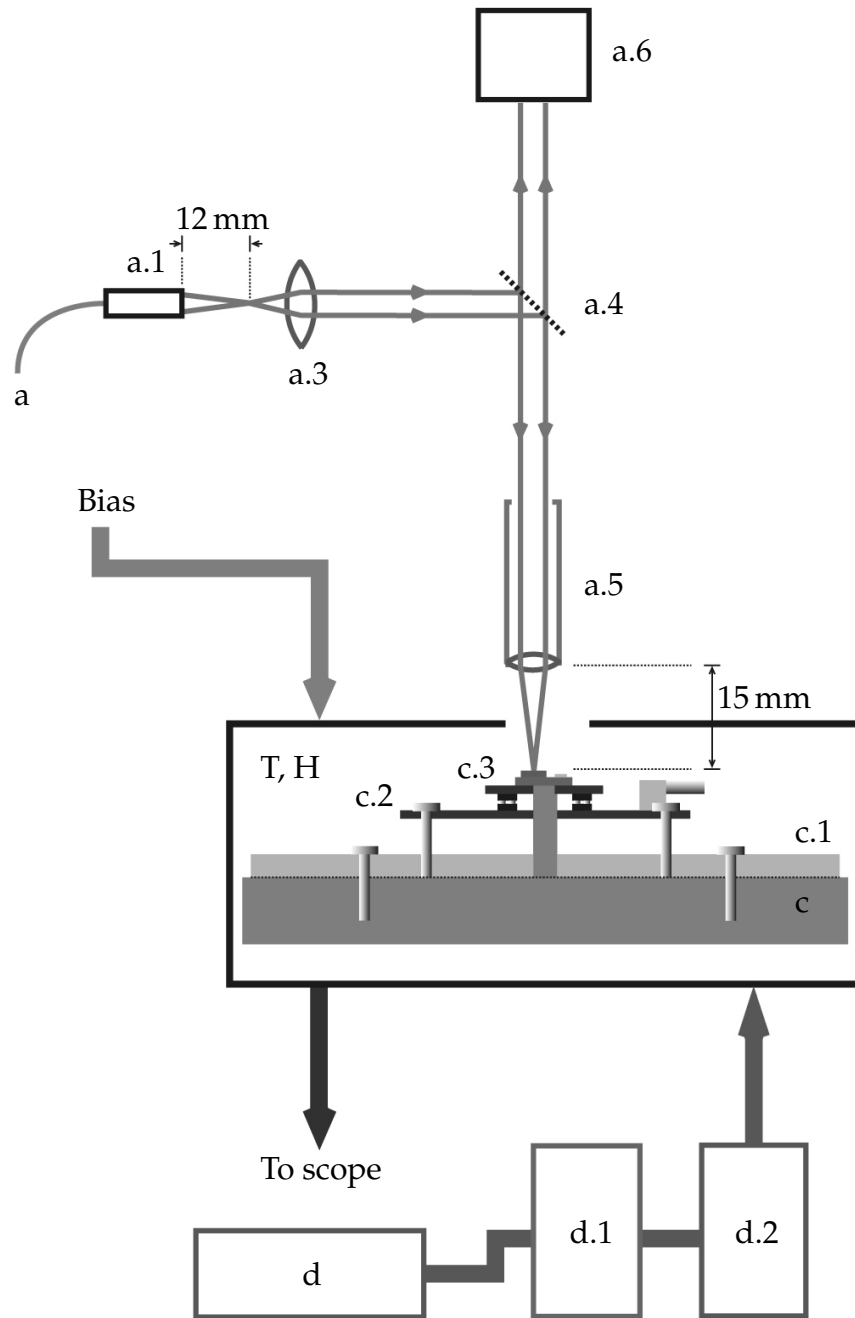
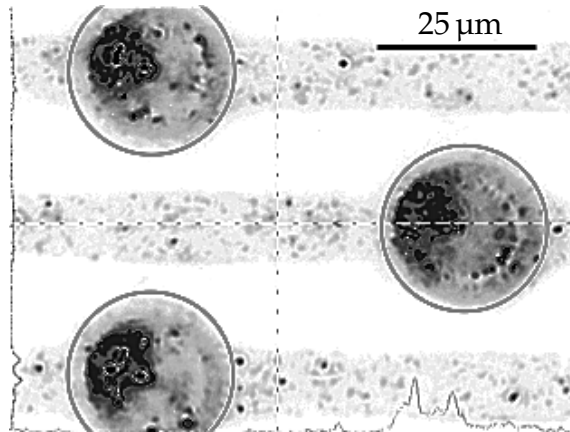
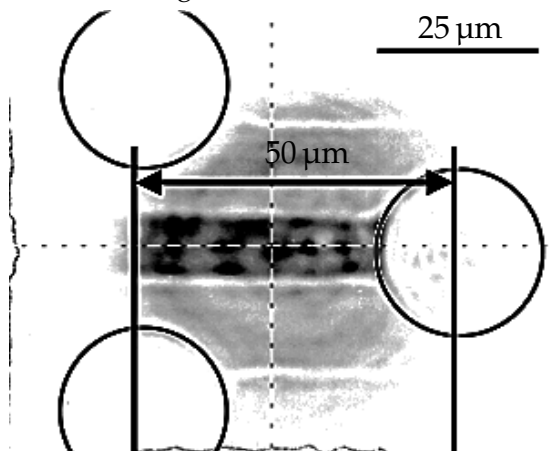


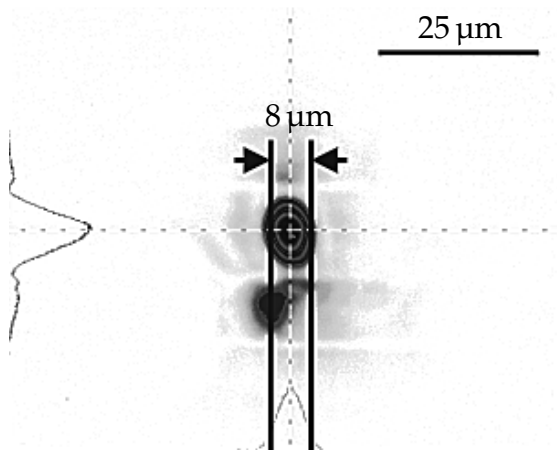
Figure 4.8: A schematic diagram of the experimental set-up. Its key features are described and referred to in the main body of the text. The temperature of the sensor and humidity within the lower chamber were monitored by a thermistor (T) and humidity sensor (H).



(a) Image of the sensor surface using microscope lighting. Circular electrodes (circled) and the aluminium lines connecting them are visible.



(b) Image of the sensor surface using a 50 µm diameter laser spot. The aluminium line crossing the centre of the image has a higher reflectivity than the surrounding silicon bulk.



(c) Image of the sensor surface with an 8 µm diameter laser spot shining onto the silicon bulk. There is a secondary peak due to a small misalignment in the set-up's optics, this is enhanced due to its reflection in the aluminium line.

Figure 4.9: Images from the *Spiricon* beam profiler of the non-irradiated sensor surface.

4.7.1 Laser set-up

The laser used for signal measurements was a *PicoQuant* pulsed diode-laser with maximum power output of 20 mW, pulse width < 1 ns, frequency of 10 MHz, and wavelength of 1060 nm. Since the penetration depth of light at this wavelength in silicon is ~ 900 μm , it is reasonable to use infra-red light to simulate minimum ionising particles [73]. During measurements the power of the laser was set to 80 % of its maximum value. It required several minutes to stabilise before its output remained within ± 3 % of the value set [74].

The light was fed through a fibre optic cable (a) into a fibre focuser (a.1), which could focus the light to a minimum beam diameter of 8 μm , before a lens (a.3) collimated the beam into the microscope's optics. There, a splitter (a.4) reflected a fraction of the light into the microscope's objective (a.5) which focused it onto the sensors's surface.

The intensity of light reflected off the sensor's surface was measured with a *Spiricon* beam profiler (a.6). It was calibrated by first removing all light (background and laser), and setting the measured intensity to a value of 0, before focussing the laser onto the sensor's aluminium read-out pad and setting the measured intensity to a value of 1. ² Beam spots of various diameter could be achieved in moving lens (a.3) parallel to the beam. Figure 4.9 compares two images of the beam spot captured by the beam profiler, one with a diameter of 8 μm and the other with a diameter of 50 μm .

4.7.2 Sensor mounting

During measurements, the sensors were secured to the probe station's thermal-chuck (c). Each sensor was mounted on its own 'portable' PCB (c.3) with gold plated male pin connectors on its backside. These made a secure mechanical and electrical connection to a 'fixed' PCB (c.2) mounted on the chuck via an aluminium plate (c.1). A copper pillar made direct contact between the chuck and the sensor, where at abutting surfaces thermal grease was used to improve thermal conductivity. With this set-up, an accurate position of the sensor could be maintained to ~ 2 μm with respect to the microscope's objective.

4.7.3 Sensor bias and read-out

A schematic diagram of the electrical connections to the sensor are shown in Figure 4.10. A *Keithley 2410* source meter provided the bias, feeding on to the fixed

²The reflectivity of light with wavelength 1060 nm off of aluminium is reported to be $> 90\%$ [75].

PCB through a high frequency filter, before passing on to the sensor.

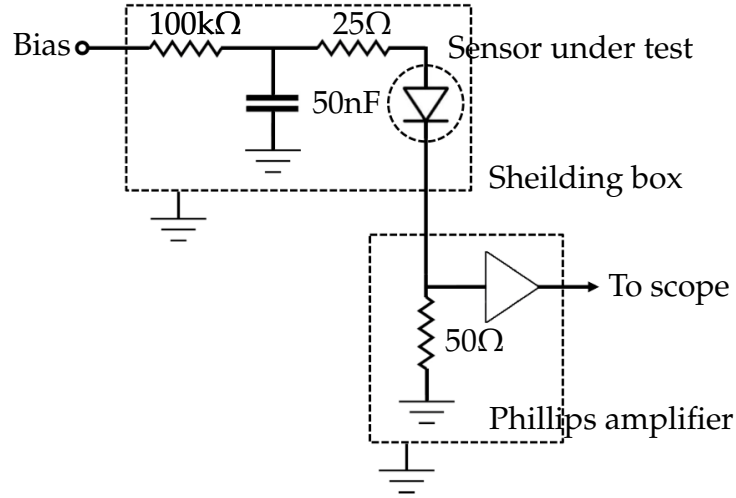


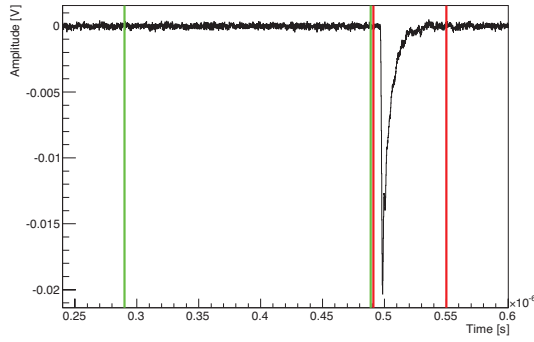
Figure 4.10: Schematic diagram of the electrical connections to the sensor and read-out.

A *Phillips* scientific current amplifier, with gain of ten and rise time of 180 ps, was used to amplify the signal. Its output fed into a 3 GHz bandwidth *LeCroy* oscilloscope, which output a voltage-time trace. The integral of the voltage-time trace was directly proportional to the ionised charge. From here on, the word signal will be used when referring to this integral value.

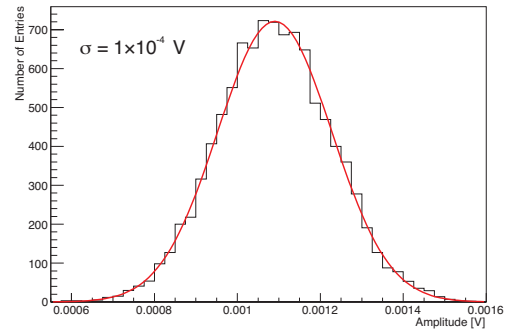
For a sensor biased at 20 V, Figure 4.11 a) shows the voltage-time trace, averaged over 256 pulses of the laser. Before integration, a pre-pulse region of length 200 ns, highlighted in green, was analysed to determine the trace's offset and offset uncertainty. This was measured to be $(1.1 \pm 0.1) \times 10^{-3}$ V for the example trace, as shown in 4.11 b). After correcting for the trace offset, the pulse was integrated to determine the signal. Uncertainties on the signal were determined through randomly varying the offset within its uncertainty (assuming poisson statistics) and integrating. After a total of 10 000 iterations, the resulting signal distribution is shown in Figure 4.11 c), with a measured mean value of $(1.3 \pm 0.1) \times 10^{-10}$ V s. A typical pulse length was 10 ns to 40 ns depending on the sensor's capacitance. An integration time of 60 ns was used for all the measurements.

4.7.4 Temperature and dry air

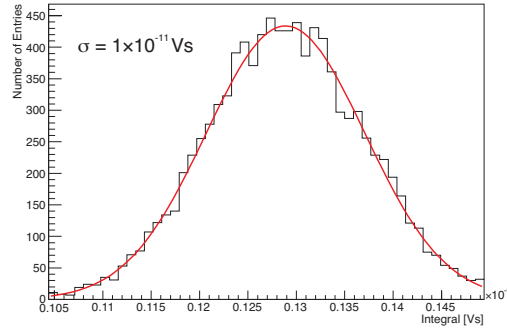
It is important for laboratory measurements on heavily irradiated sensors to be performed at temperatures below 0 °C. This reduces any annealing effects, and when biased, keeps the leakage at an acceptable level. With this in mind, the set-up was designed so that sensors could be held at a temperature down to −20 °C,



(a) Voltage-time trace.



(b) Measured offset.



(c) Signal distribution.

Figure 4.11: The voltage-time trace, averaged over 256 pulses of the laser, for a sensor biased at 20 V. The pre-pulse and integration regions are bordered by green and red bands respectively in a). b) shows the offset distribution and c) the final signal distribution with mean value of $(1.3 \pm 0.1) \times 10^{-10}$ V s, having followed the process described in the text.

achieved through contact with the thermal chuck. During measurements, the temperature was monitored with a PT1000 thermistor on each portable PCB. To stop condensation forming, the lower chamber of the probe station was continuously flushed with dry air of dew point -40°C . An adequate flow was produced using a compressor (d), adsorption drier (d.1) and holding tank (d.2).

4.7.5 Sensor and beam profiler signal

The laser power incident, P_i , on the sensor's surface can be parametrised by:

$$P_i = P_a + P_r \quad (4.2)$$

where P_a and P_r are the laser power absorbed and reflected by the sensor respectively. Since power and intensity are directly proportional, Equation 4.2 can be written:

$$P_i = AI_a + BI_r \quad (4.3)$$

where I_a and I_r are the light intensity absorbed and reflected respectively. The signal measured in the silicon, S , is directly proportional to I_a , and the signal measured in the beam profiler, R , directly proportional to I_r , hence Equation 4.2 becomes:

$$P_i = A'S + B'R \quad (4.4)$$

For all measurements P_i was kept constant, A and B are proportionality constants, and so S can be parametrised by:

$$S = A'' - B''R \quad (4.5)$$

With a spot diameter of $8\mu\text{m}$, initial signal measurements were performed at several locations on the sensor A0's surface, including cells at its centre and most external edge. The spot diameter was then increased to $50\mu\text{m}$, and the measurements repeated. On having completed signal measurements with the entire sensor connected, the segment S_4 was isolated (c.f. Section 4.5), and measurements performed at several locations along its length, again with varying spot diameters of $8\mu\text{m}$ and $50\mu\text{m}$.

Figure 4.12 compares all these measurements having been fit with Equation 4.5. The shaded region marks the fit uncertainty. Measurements on the entire sensor and S_4 are marked by circles and triangles respectively. Spot diameters of $8\mu\text{m}$ are represented by solid markers and $50\mu\text{m}$ by hollow markers. By defini-

tion, the value of R is equal to 1 when all light is reflected and 0 when all light is absorbed. This varied with measurement position and spot diameter, due to the presence of aluminium lines on the sensor's surface reflecting various amounts of light.

The measurements confirmed two key points:

1. That segmentation had no effect on the measured signal, as measurements before and after were comparable.
2. The beam for both spot diameters was contained within the cell's active volume. Otherwise, a higher signal would have been measured from the entire sensor compared to S_4 .

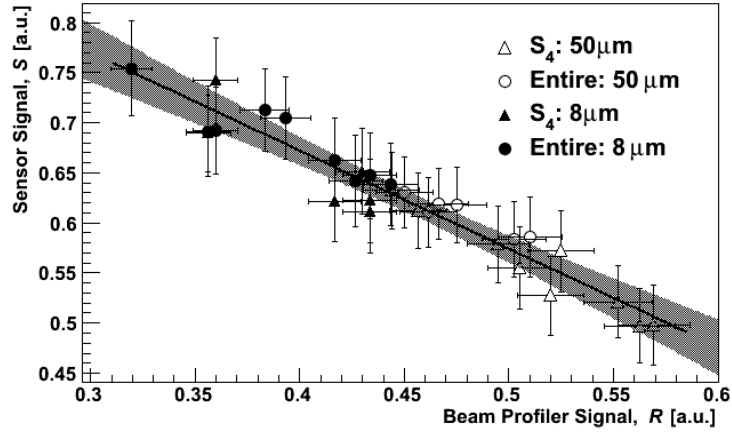


Figure 4.12: Signal from the non-irradiated sensor versus signal from the beam profiler. Equation 4.5 has been fit to the data, with the fit uncertainty shaded in grey. Measurements were made with beam spot diameters of 8 μm (solid) and 50 μm (hollow) on the entire sensor (circle) and S_4 (triangle).

4.8 Irradiation

Four of the test sensors were sent to the Los Alamos Neutron Science Centre (LANSCE) for irradiation, where an 800 MeV proton beam with typical beam current of 60-80 nA was located in the Blue Room (Target 2) at the Weapons Neutron Research (WNR) facility [76]. Sensors were placed in the beam for varying periods of time to receive a desired fluence. Initially this was approximated using a scintillator to count the number of beam pulses. Later it was accurately determined from the activity of aluminium foils placed with the sensors [77]. Figure 4.13 a) shows the mounting box used during the irradiation. The beam entered

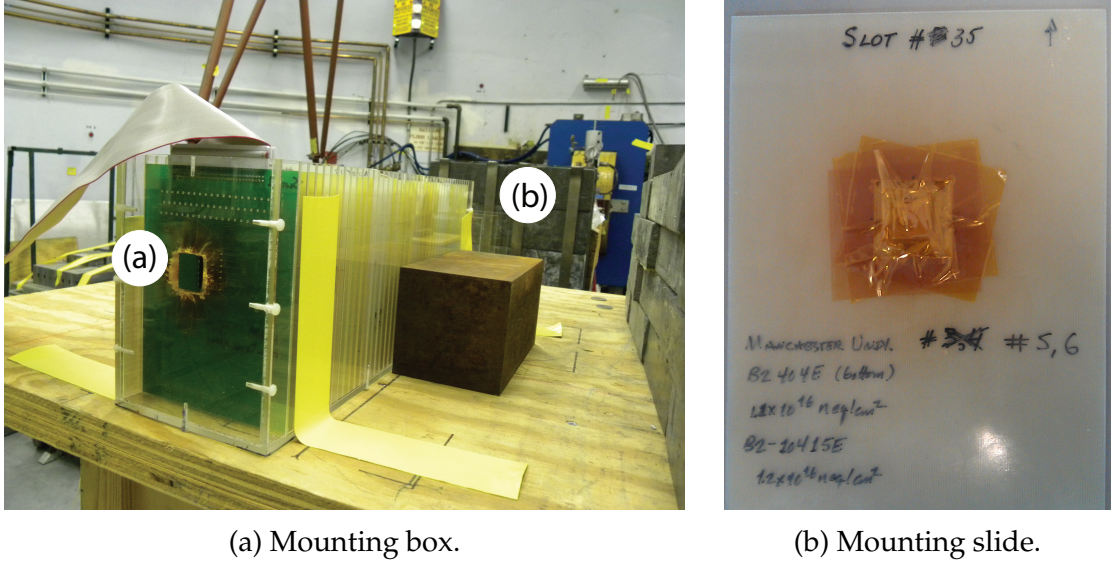


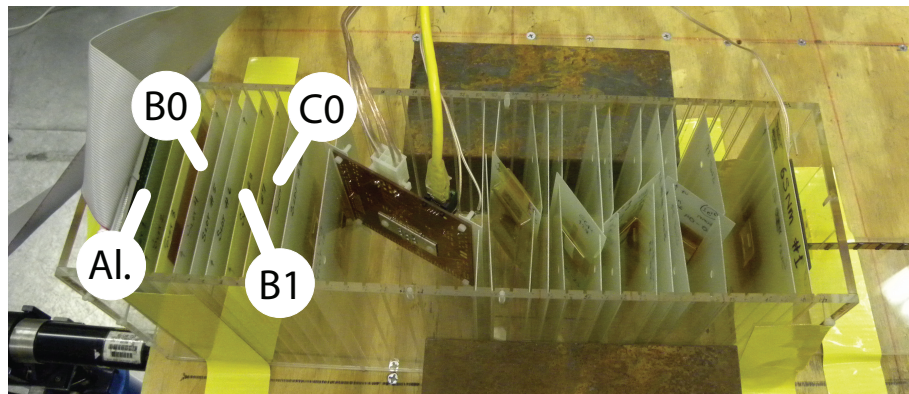
Figure 4.13: Mounting box and slides used to hold devices in the proton beam during the irradiation.

the box at (a), passed along its central axis through the devices, before exiting at the opposing side and being absorbed in a beam stop (b). The scintillator used for pulse counting was positioned at the beam's exit from the box. Devices were mounted on to plastic sleeves using kapton tape, as shown in Figure 4.13 b). These slotted into the mounting box. Figure 4.14 shows the box set-up for the medium and high fluence runs in which the test sensors were placed. The positions of each sensor along with that of the aluminium foil used for fluence measurements are labelled. The measured proton fluence was converted into a 1 MeV n_{eq} fluence using NIEL scaling (c.f Chapter 3). Table 4.2 lists each sensor along with the proton and the equivalent neutron fluence it received. Fluence measurements and associated errors were determined at The University of New Mexico [77].

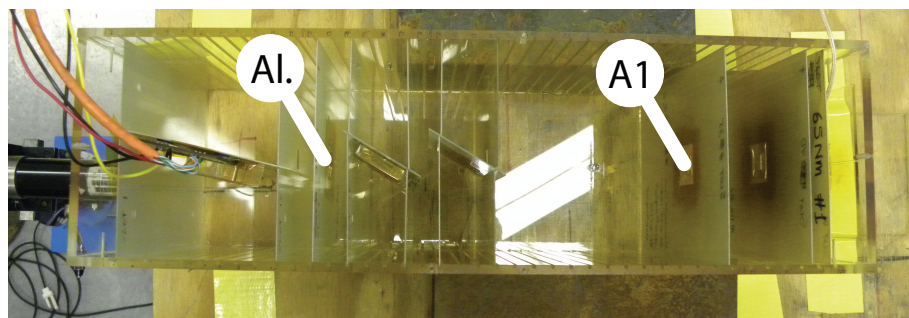
Sensor	Proton fluence ($p \text{ cm}^{-2}$)	Neutron fluence ($n_{eq} \text{ cm}^{-2}$)
A0	0	0
C0	$(3.1 \pm 0.3) \times 10^{15}$	$(2.2 \pm 0.2) \times 10^{15}$
B0	$(6.2 \pm 0.6) \times 10^{15}$	$(4.4 \pm 0.4) \times 10^{15}$
B1	$(6.2 \pm 0.6) \times 10^{15}$	$(4.4 \pm 0.4) \times 10^{15}$
A1	$(3.0 \pm 0.2) \times 10^{16}$	$(2.1 \pm 0.2) \times 10^{16}$

Table 4.2: Table showing the proton and equivalent neutron fluencies received by each sensor.

Unfortunately at some point during their transportation back from Los Alamos to Manchester, the the sensors were mechanically damaged. This included scratches to their surface, causing electrical shorts, in addition to several visible breaks



(a) Medium fluence.



(b) High fluence.

Figure 4.14: Set-up of the mounting box for a) the medium fluence and b) high fluence runs. The positions of the test sensors and that of the aluminium foil (Al.) are labelled. In both cases, the proton beam enters the box from the left-hand side of the image.

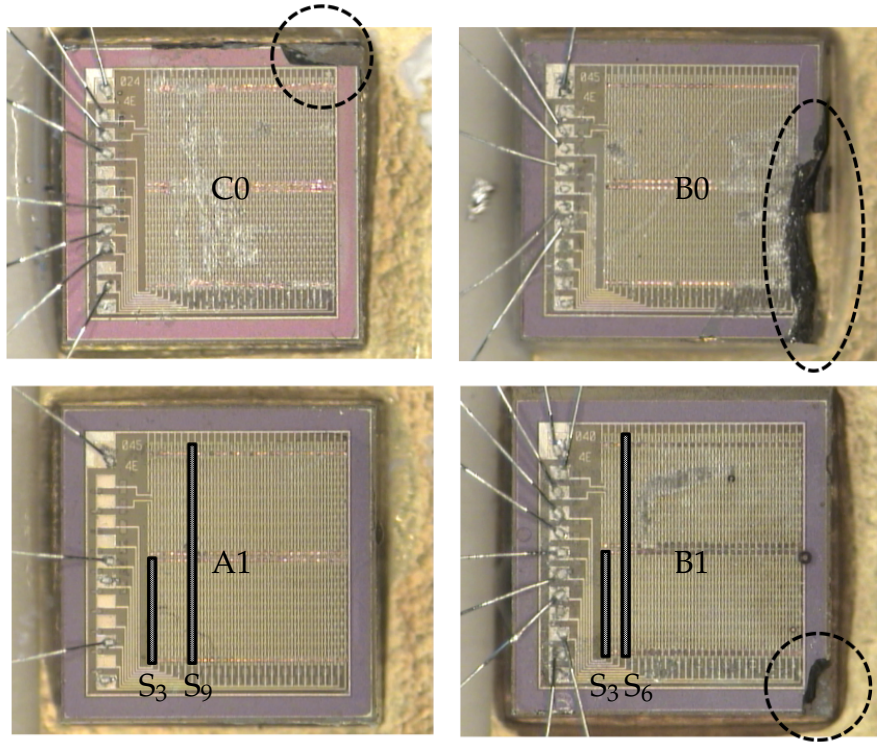


Figure 4.15: Images of sensors after irradiation. Unfortunately the sensors were mechanically damaged when being transported from Los Alamos back to Manchester. Visible breaks to the silicon wafer are circled. Electrical shorts were removed by segmenting each sensor. In doing this, two segments were recovered on both sensors A1 and B1. No segments were recovered on sensors C0 and B0.

in the silicon wafer. For each sensor, initial IV measurements showed immediate diode breakdown. In an attempt to recover any working regions, the sensors were segmented. A probe station needle was used to scratch off the surface metallisation in-between read-out pads. Electrical isolation of each segment from the others was confirmed with resistivity measurements. Once isolated, IV measurements were repeated. The segments that did not show immediate diode breakdown are labelled in Figure 4.15. Unfortunately all segments on B0 and C0 showed immediate diode breakdown, however, two segments were recovered on both A1 and B1.

For subsequent irradiations, the device mounting was improved. Nylon loops were placed around each device, before being covered with kapton tape. There is no adverse effect associated to either material when exposed to proton or neutron irradiation. Figure 4.16 shows the more robust mounting.

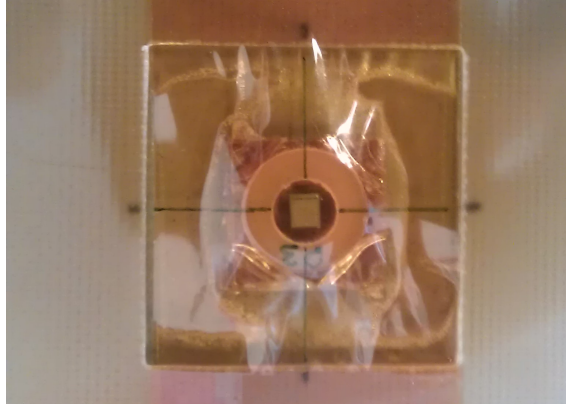


Figure 4.16: The improved sensor mounting for subsequent irradiations. A nylon ring is used to surround the sensor, positioned at the centre of the image, and covered in kapton tape for protection.

4.9 Sensor characterisation after irradiation

Figure 4.17 compares the IV measurements from the four recovered segments on sensors B1 and A1 taken after irradiation. To allow for a comparison to those measured before irradiation (c.f. Figure 4.7), all measurements have been temperature corrected to 20 °C and normalised to the volume of a non-segmented sensor.³ Note the change in scale from μA to mA . There is a good agreement between measurements made on different segments of the same sensor, indicating that the radiation damage is approximately uniform throughout the bulk.

After irradiation, the leakage current is dominated by generation in the bulk volume. Therefore from Equation 3.12, the radiation induced volumetric leakage current is linearly proportional to fluence, Φ , given by:

$$\frac{I}{V} = \alpha \Phi \quad (4.6)$$

Thus it is possible to confirm the fluence received by a sensor in measuring its leakage current at full depletion. Simulations on sensors with the same inter-electrode spacing after irradiations of $10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ have shown full depletion at 150V [79]. Figure 4.18 shows, for segments on devices A1 and B1, the average volumetric current measured over the range 130 V to 170 V versus fluence. Equation 4.6 has been fit to the data, and its uncertainty shaded in grey. The damage constant α deduced from the fit is $(6.2 \pm 0.5) \times 10^{-17} \text{ Acm}^{-1}$. After beneficial annealing, eighty minutes at 60 °C or two weeks at room temperature, the damage constant has previously been measured to be $4 \times 10^{-17} \text{ Acm}^{-1}$ [80]. The

³The leakage current is heavily dependent on temperature due to thermal excitations aiding electrons across the band gap. To allow for comparison between measurements taken at different temperatures, it is common for IV measurements to be temperature corrected using a well understood parametrisation [78].

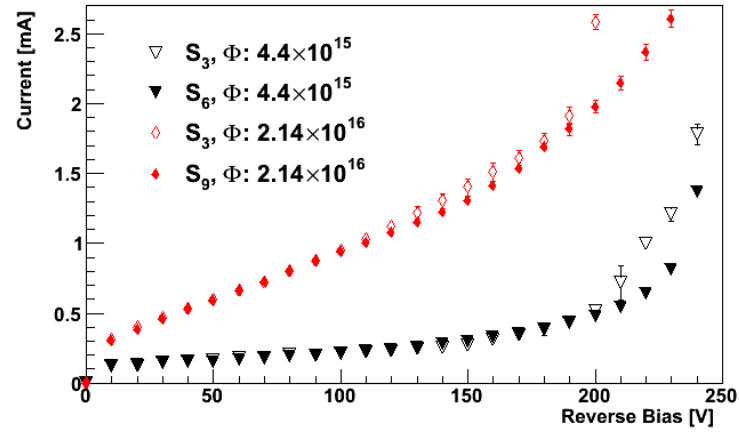


Figure 4.17: IV measurements after irradiation for segments on sensors B1 and A1. All measurements have been temperature corrected to 20 °C and normalised to the volume of the non-segmented sensor.

active volume after segmentation is estimated by taking the product of the unit cell volume and the number of cells connected to the segment. In reality, there is likely to be some unknown additional fraction due to electric field leakage within the device. Hence, the discrepancy between the measured value of α and $4 \times 10^{-17} \text{Acm}^{-1}$ is most likely due to the difficulty in accurately determining the active volume of each segment.

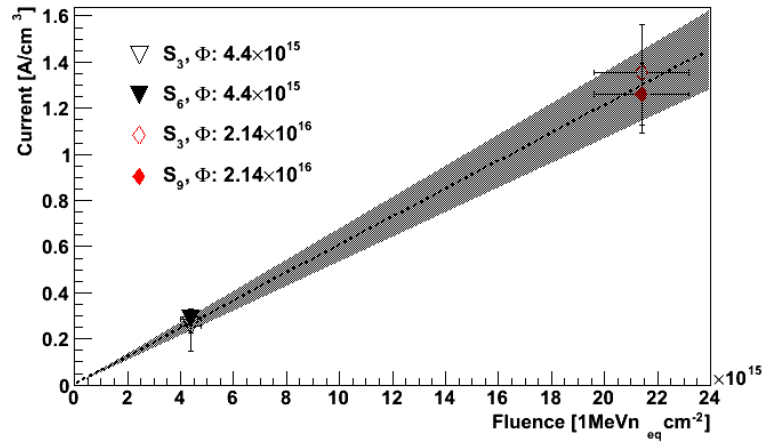


Figure 4.18: Measured average volumetric leakage current over the range 130 V to 170 V at 20 °C versus fluence.

4.10 Signal measurement

When performing signal measurements on irradiated sensors, to reduce any effects of localised damage, a relatively large spot diameter of $50\mu\text{m}$ was used. This ensured an average signal response from the cell. Signal measurements were repeated at several locations along the segment's length. All measurements were taken within a sensor's sensible operating range as determined from the IV curves in Figure 4.17.

Figure 4.19 compares the irradiated and non-irradiated signal measurements. The signal from each irradiated sensor at measured R , was normalised by the expected signal from the non-irradiated sensor (extracted from the fit) at the same value of R . This normalised value is a reasonable approximation of the SE (c.f. Section 3.9). An example signal comparison at $R \sim 0.54$ is given in Table 4.3. Altogether, the average SE measured for a fluence of $4.4 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ at 220 V was $(76 \pm 6)\%$, and for a fluence of $2.14 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ at 220 V was $(50 \pm 5)\%$. A comparison voltage-time trace can be seen in Figure 4.20. Both the non-irradiated and the most heavily irradiated sensors are shown. The traces have not been averaged over 256 pulses of the laser (c.f. Section 4.7.3). Even so, the signal pulse is clearly visible over random trace fluctuations.

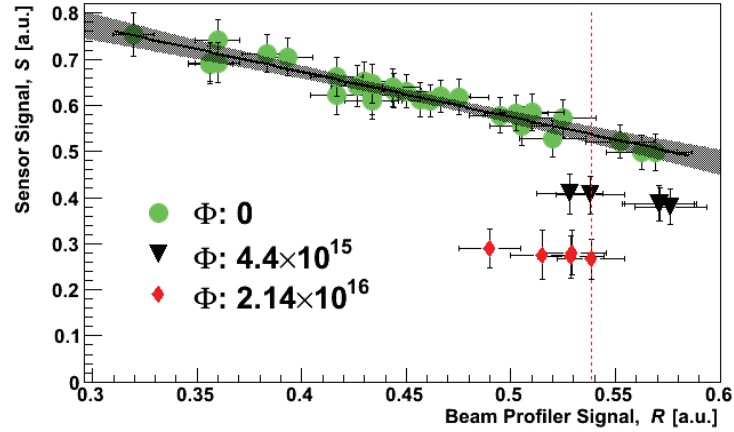


Figure 4.19: Signal from the sensor versus signal from the beam profiler for the irradiated sensors. Measurements from the non-irradiated sensor and fit from Figure 4.12 have been included for comparison. Table 4.3 compares signal measurements at $R \sim 0.54$.

Previous SE measurements on identical full-3D sensors have been made up to a maximum fluence of $1.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ [68]. Figure 4.21 shows these in addition to the above, where Equation 3.16 has been fit to the data. Since L , and Φ are known, taking v_D to be the saturated drift velocity, equal to 10^7 cm s^{-1} [81], it

Fluence ($n_{\text{eq}} \text{ cm}^{-2}$)	Sensor Signal, S (a.u.)	SE (%)
0	0.54 ± 0.02	100
4.4×10^{15}	0.40 ± 0.04	74 ± 8
2.14×10^{16}	0.27 ± 0.04	50 ± 8

Table 4.3: Comparison of irradiated and non-irradiated signal measurements at $R \sim 0.54$.

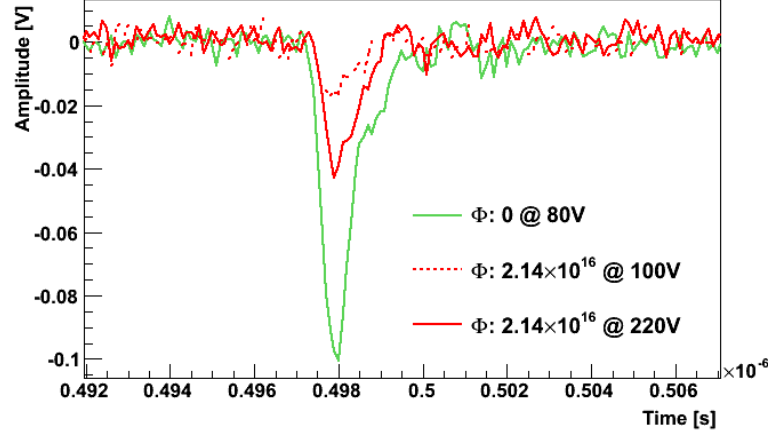


Figure 4.20: The non-averaged voltage-time trace from an irradiated and non-irradiated sensor. Different bias voltages are shown for comparison.

is possible to determine a value for β from the fit. Since the n^+ and p^+ implants have a finite width, the actual inter-electrode spacing is smaller than the geometric value L . This offset has previously been measured to be $\sim 22 \mu\text{m}$, and has been accounted for [59]. The calculated value of β is equal to $(2.5 \pm 0.5) \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$. A value of $(4.5 \pm 0.2) \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ and $(2.8 \pm 0.1) \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$, before and after annealing respectively, are quoted in [52]. The value calculated is slightly lower, but in agreement with [52].

4.11 Conclusions

Several full-3D test sensors were irradiated up to a fluence of $2.14 \times 10^{16} n_{\text{eq}} \text{ cm}^{-2}$. This is equivalent to the cumulative fluence predicted at a distance of $\sim 35 \text{ mm}$ from the interaction point in a detector such as ATLAS, after approximately 10 years of operation at the HL-LHC. Electrical characterisations were performed before and after irradiation, where an increase in leakage current was observed. After sensor segmentation, signal measurements were performed using an infra-red laser set-up to simulate the charge ionised by a MIP. A beam

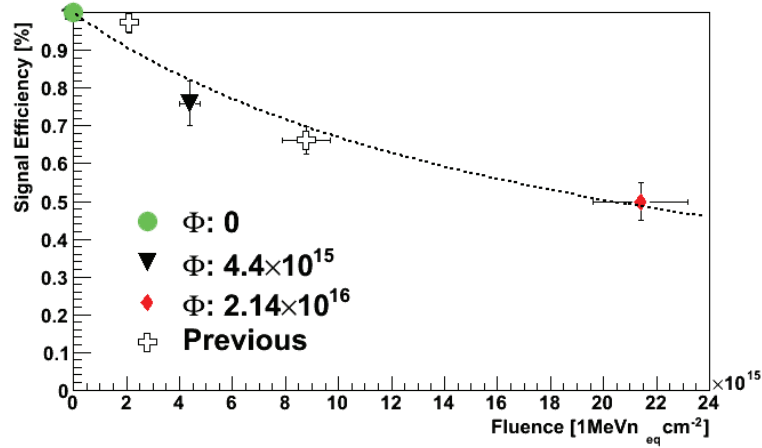


Figure 4.21: SE versus fluence. Equation 3.16 provides a reasonable fit to the data.

profiler monitored the beam spot diameter, position and reflection intensity on the sensor's surface. There was a negative correlation observed between the measured reflection intensity and the signal measured in the silicon. Hence an accurate comparison could be made between signals taken at different locations on different samples. A SE for each fluence was measured by comparison to a non-irradiated sensor. The sensor irradiated to the highest fluence showed a measured SE of $(50 \pm 5)\%$.

Previous measurements on partial-3D sensors up to this fluence have shown comparable results. With a square array of $80 \mu\text{m} \times 80 \mu\text{m}$, equating to an inter-electrode spacing of $56 \mu\text{m}$, a SE of 53 % at 300V and 70 % at 425V have been measured, [69] and [66]. Table 4.4 compares these to the full-3D measurements. Charge multiplication is a phenomenon only present in partial-3D detectors (c.f. Section 4.3.1), explaining the surprisingly high SE measurement of 70 % at 425 V. Even at an equivalent bias, it is unlikely a SE much above the measured value of 50 % would be observed in a full-3D detector.

Sensor type	Bias voltage (V)	SE (%)
Full-3D	220	50
Partial-3D	300	53
Partial-3D	425	70

Table 4.4: Comparison of full-3D and partial-3D SE measurements. All sensors received a fluence of $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The partial-3D measurements can be found in [69] and [66].

A MIP is expected to produce 22.5 ke of charge when passing through $300 \mu\text{m}$ of silicon. With a measured SE of 50% at 220 V, one would expect to collect

11.25 ke after a radiation fluence of $2 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. This signal is well above the operational threshold (3 ke) of the Front End read-out chip (FEI4) designed for the IBL, and on which the next generation of read-out chips are based [82].

Future work shall focus on irradiation of the combined sensor and read-out chip module, allowing for an accurate determination of the expected noise after such heavy fluencies. Since charge multiplication effects, and more importantly, their stability, are still not fully understood, the continued development of both full-3D and partial-3D technologies is important; especially since future improvements in fabrication techniques are likely to allow for smaller diameter electrodes with greater charge collection efficiency.

Chapter 5

3D diamond – for particle tracking

5.1 Introduction

In comparison to silicon, diamond is intrinsically a more radiation tolerant material. This is due primarily to the comparatively large amount of energy required to break atoms from its crystal lattice (c.f. Chapter 3). Furthermore, it has several other qualities that make it (arguably) a better material for high energy particle detection, including a higher thermal conductivity and lower dielectric constant [83].^{1 2} As a result, it has previously been used for particle detection in high radiation regions of the ATLAS experiment, yet only in a conventional planar geometry [85] [86]. The previous chapter detailed how the adoption of a 3D geometry improves a detector's radiation tolerance compared to a planar geometry. Thus, if this principle were applied to diamond, it might result in an 'ultra-radiation tolerant' detector. With this in mind, this chapter details the development, fabrication and testing of the first 3D diamond detector with multi-channel read-out for the purpose of particle tracking.

In principle, a diamond detector could be fabricated from either natural or synthetic diamond, however, for reasons of practicality and material consistency, in general synthetic diamond is used.

¹When silicon is operated as a detector, power dissipated in the material due to the leakage current, generates heat. Over prolonged periods of operation, this heat has to be removed, often requiring complicated technical solutions like micro channel cooling within the sensor bulk as proposed for future upgrades [84]. With diamond, due to its low leakage current and much higher thermal conductivity, heat removal is potentially much simpler.

²The dielectric constant is directly related to material capacitance, which in turn is related to the detector noise.

5.2 Synthetic diamond

Plates of synthetic diamond are grown using a Chemical Vapour Deposition (CVD) process [87]. At high temperatures (> 2000 K) a mixture of methane (containing carbon), hydrogen and oxygen gas are deposited over a substrate surface, inducing material growth. With this method, two types of diamond can be formed: Single Crystal (SC) and Polycrystalline (PC), depending predominantly on the substrate used. In both cases growth rates are typically around $\sim 1 \mu\text{m h}^{-1}$ for detector grade material.

5.2.1 SC diamond

SC diamond is formed when the substrate itself is SC. Growth occurs homo-epitaxially (ordered growth with the same crystal orientation) and the new material, like the substrate, is very pure, with few lattice defects. However, plate sizes are currently limited to $\sim 8 \text{ mm} \times 8 \text{ mm}$, due to difficulty in producing substrates with larger area [87].

5.2.2 PC diamond

PC diamond is formed when growth occurs from a non diamond substrate, typically silicon. Initially, a large number of crystal seeds form on the substrate surface. With continued deposition, these grow together, forming columnar single crystals with grain boundaries in-between. The lateral width of each crystal increases in the growth direction, from $\sim 2 \mu\text{m}$ at the substrate side to $\sim 100 \mu\text{m}$ at a thickness of $500 \mu\text{m}$. Figure 5.1 shows a cross-section image of a PC diamond. After growth, both surfaces are polished to smooth and remove material. At the substrate side, the first $100 \mu\text{m}$ of diamond is considered 'low-grade', due to the small lateral width of the crystals, and is removed. In using silicon as a substrate, there is essentially no limitation on growth area, and plate sizes greater than $10 \text{ cm} \times 10 \text{ cm}$ can be produced.

5.3 Charge collection properties

A basic introduction to the theory of semiconductor detectors is given in Chapter 3. With regards to charge collection, an important material parameter is the CCD. In synthetic diamond impurities, lattice defects and grain boundaries are all sources of carrier traps reducing the CCD. For this reason during the CVD growth process, impurities are kept very low, typically < 1 ppm for nitrogen in

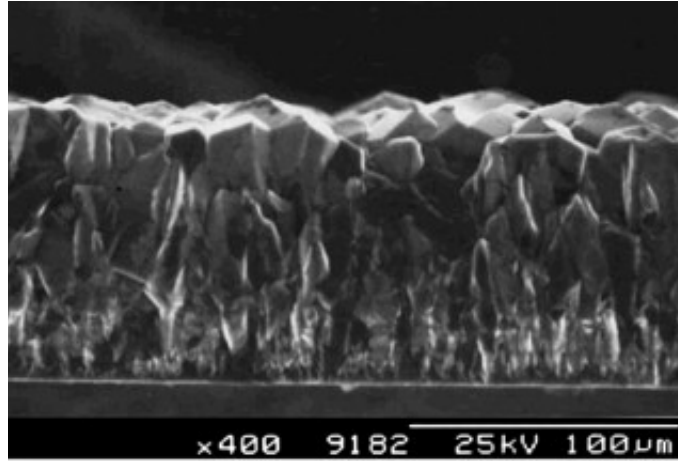


Figure 5.1: A cut-away of crystal growth in PC diamond. Staring from the substrate side (image-bottom), the lateral crystal width increases in the upwards growth direction [88].

‘detector grade’ material. However, unfortunately lattice defects are unavoidable and, due to slight differences in growth techniques, in general more are present in PC than SC diamond [87]. Finally, grain boundaries in-between columnar crystals are only present in PC diamond. The last two factors give PC a shorter CCD compared to SC, typically $\sim 300\text{ }\mu\text{m}$ compared to $> 1\text{ mm}$. Grain boundaries also affect the uniformity of CCD, hence in PC diamond the amount of signal induced by the passage of a particle is often dependent on the point at which it traversed the detector [89]. Note, although PC diamond has in general a shorter CCD than SC, with continued radiation exposure, both experience the same rate of damage.

5.3.1 Priming

In synthetic diamond, previous measurements have shown the CCD to increase with exposure to small amounts of radiation, where after some time a maximum value is reached [89]. This is a peculiar effect, attributed to the gradual filling of deep level traps by free charge carriers induced by the radiation. As traps become filled, the lifetime of free charge carriers, and hence the CCD, increases until an equilibrium is reached. The effect can be reversed with exposure to UV light. Therefore when performing measurements with a diamond detector it is common to ‘prime’ beforehand. This involves exposing it to a radiative source shortly before measurements, with the aim of filling deep level traps. Once primed, the detector is kept in a light tight environment to stop the effect from being reversed.

5.4 Adopting a 3D geometry

Having briefly described the charge collection properties of synthetic diamond, adopting a 3D geometry would potentially have two main benefits:

1. Comparable performance from SC and PC diamond detectors: Using an inter-electrode spacing less than the CCD in PC would potentially allow for full charge collection. This would also improve signal uniformity.
2. Increased radiation tolerance of both SC and PC diamond detectors. Potentially producing an ultra-radiation tolerant detector.

A novel way of fabricating the 3D geometric structure in diamond is to use a laser to implant columnar ohmic-electrodes. With laser irradiation the diamond under goes a phase transition into an ohmic-material consisting of diamond-like carbon, amorphous carbon and graphitic material [90]. The mechanism behind this phase transition is described in [91]. The first prototype 3D diamond detector was produced in this way, using a nano-second laser [92]. However, due to the laser's relatively long pulse length, the electrodes formed were non uniform along their length and had large diameters ($> 20 \mu\text{m}$). Furthermore, stress in the crystal lattice was sufficiently high to cause cracks in the diamond plate. Even so, using a 15 keV photon micro-beam as ionising radiation, the detector was shown to have a charge collection dependent on proximity to electrodes.

Recent studies into using a laser with shorter pulse length (femto-second) have shown much improved electrode formation, with reduced aspect ratio, consistent uniformity and reduced stress in the crystal lattice [90]. With this in mind it was hoped an improved prototype 3D diamond detector might be fabricated following the techniques described in [90], using a femto-second laser based in the Manchester Photon Science Institute.

5.5 Laser set-up and electrode formation

The femto-second laser was a Coherent Libra Ti-Sapphire, with a wavelength of 800 nm, TEM₀₀ beam mode and a pulse duration of 100 fs. Its pulse repetition was fixed at 1 kHz. In order for it to be used to fabricate electrodes, a set-up, as shown in Figure 5.2, was constructed. It consisted of several directional mirrors, lenses and filters fixed onto a stable platform. With reference to the diagram, the beam exited the laser unit at (a). On exiting it passed through a neutral-density filter attenuator (b), used to adjust the beam power, before being directed through several lenses and focussed onto the diamond plate (d). The final lens

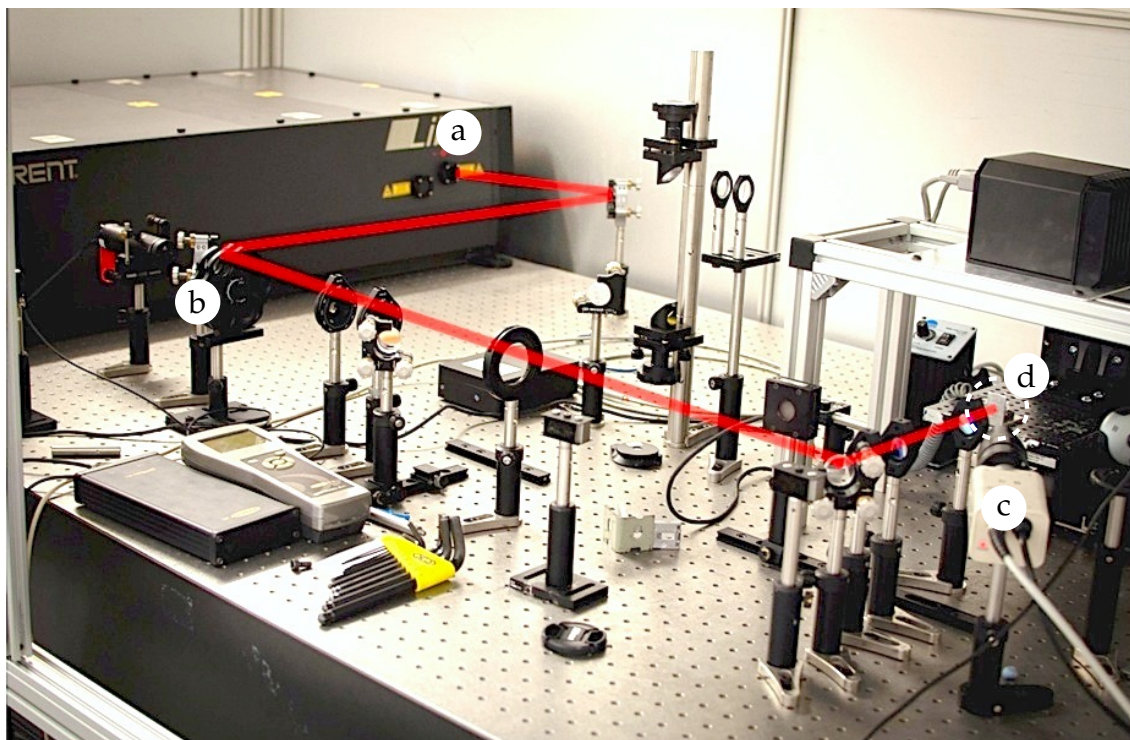


Figure 5.2: The femto-second laser set-up used for electrode production. A red line highlights the path taken by the laser beam onto the diamond surface (d).

focussed the beam down to a minimum waist diameter of $4\text{ }\mu\text{m}$, referred to as the 'beam spot'. Beam power was determined after focussing. During processing the electrode formation could be monitored using a camera mounted at (c).

The method of electrode formation is shown in Figure 5.3. With the beam spot (a) initially focussed on the back side of the diamond plate, the plate was moved in a direction perpendicular to the focal plane with a translation speed that allowed for continuous electrode growth – previous work states $10\text{ to }100\text{ }\mu\text{m s}^{-1}$, for beam fluencies of $0.5\text{ to }2\text{ J cm}^{-2}$ [90]. A complete electrode was formed when the beam spot reached beyond the front side of the diamond plate. Processing from back-to-front avoided light being absorbed by the electrode itself. A motorised 3-axis micro stage was used to move the sample with respect to the beam spot. With this, electrode arrays could be produced by repeating the process at different locations on the diamond.

The electrode formation at the laser 'entrance' and 'exit' sides was very different, as can be seen in Figure 5.4. Ohmic-material protruded from the surface at the entrance side, whereas a small crater and absence of material was observed at the exit side. Due to the lower density of the graphitic phase of carbon, a pressure build-up inside the diamond was sufficient to expel the last few microns of material before the laser spot exited.

Figure 5.5 shows four arrays drilled in SC diamond with beam fluencies of 2, 3,

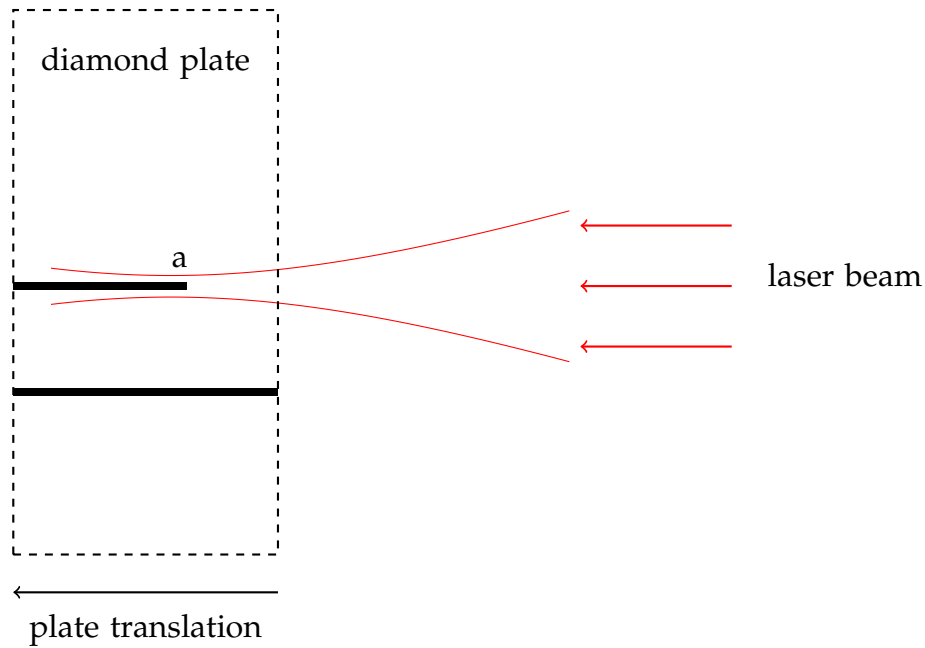
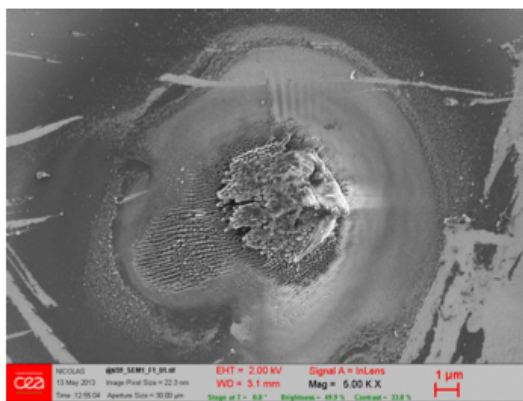
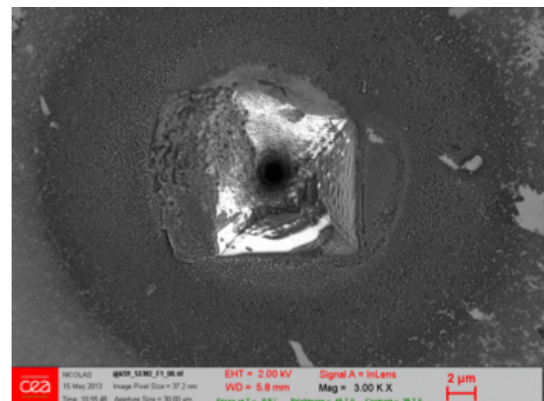


Figure 5.3: Schematic diagram of column formation in a diamond plate. The laser beam is focussed into the bulk, where the energy density at the focal point (a) is high enough to produce a phase transition. A column is formed by moving the focal point across the thickness of the material.



(a) Entrance side.



(b) Exit side.

Figure 5.4: Scanning-electron-microscope images of the laser a) entrance and b) exit sides in processing a single column. The reader should note the change in scale between images.

3.5 and 5 J cm⁻² at a translational speed of 15 µm s⁻¹. As diamond is transparent, on tilting the plate, it was possible to see the electrodes within the bulk, as shown for the highest and lowest fluence in Figure 5.6. Due to the Gaussian distribution of power in the laser beam, with higher fluence, a greater region of the beam spot was above the threshold for phase transition, and a larger diameter electrode was produced. Electrode diameters varied from approximately 5 to 10 µm.

To achieve a maximum column yield, i.e., the fraction of electrodes produced with continuous conducting path over the thickness of the diamond plate, the beam fluence and translation speed were varied within the available ranges. Large arrays of 371 columns were drilled and the yield determined. Table 5.1 lists the yield for each array along with the beam parameters used for drilling. The highest yield was measured at (93 ± 1)% with fluence of 2 J cm⁻² and translational speed of 20 µm s⁻¹.

Fluence (J cm ⁻²)	Speed (µm s ⁻¹)	Success (N)	Fail (N)	Yield (%)
2	15	342	29	92 ± 1
2	20	346	25	93 ± 1
3	15	292	79	79 ± 2
3	20	325	46	88 ± 2

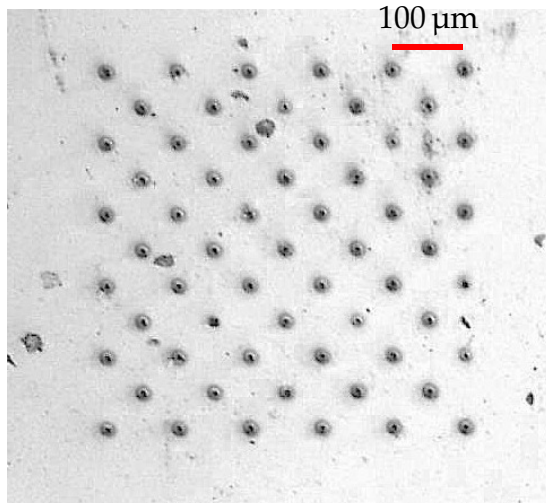
Table 5.1: Table comparing column yield for different laser parameters in PC diamond.

5.6 Prototype fabrication

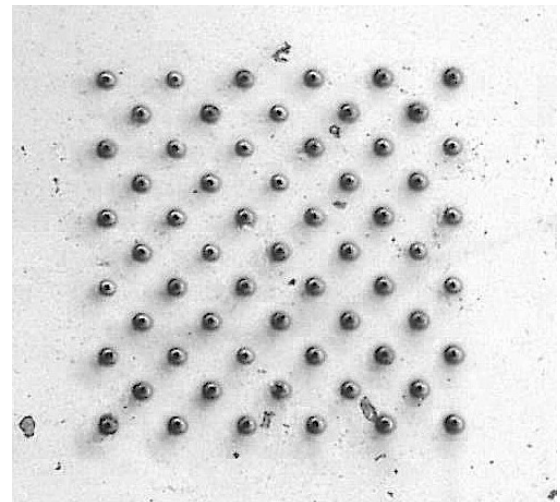
Having successfully demonstrated the formation of repeatable, uniform electrodes with a femto-second laser, it was decided a full prototype 3D detector would be fabricated and tested. The starting material was chosen to be a SC diamond manufactured by Element 6 [93]. Its fabrication into a functioning detector consisted of four key steps as described in the following sections: cleaning, laser processing, metallisation and wire bonding to read-out electronics.

5.6.1 Cleaning

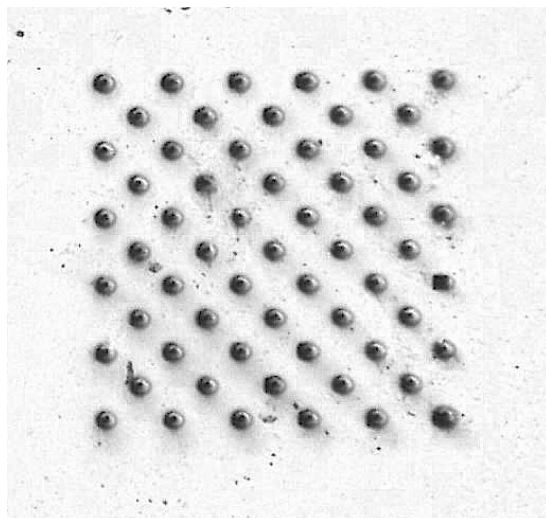
The diamond was thoroughly cleaned with mechanical polishing, reactive ion etching, and an oxidation plasma etch. The final step ensured a good surface termination, hence no surface conduction. In total, the cleaning procedure removed 10 µm from the top and bottom surfaces of the diamond sample, leaving a plate thickness of 440 µm. Across this distance full charge collection is expected in SC diamond of good quality. This was confirmed using a pad geometry and ⁹⁰Sr



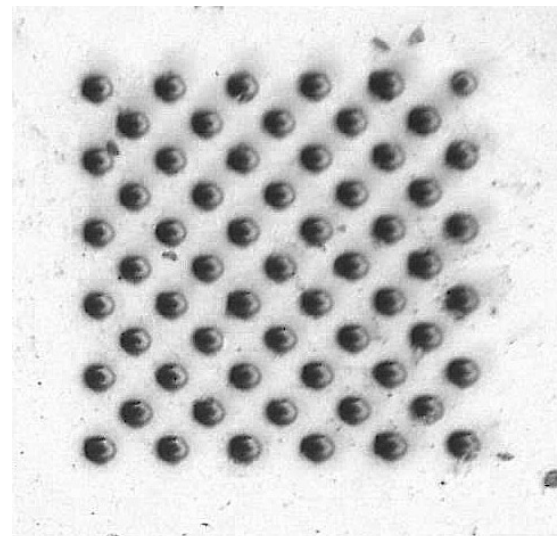
(a) Fluence of 2 J cm^{-2} .



(b) Fluence of 3 J cm^{-2} .



(c) Fluence of 3.5 J cm^{-2} .



(d) Fluence of 5 J cm^{-2} .

Figure 5.5: Comparison of column arrays drilled with increasing beam fluence. The column width increases from approximately $5 \mu\text{m}$ to $10 \mu\text{m}$ with fluencies of 2 J cm^{-2} to 5 J cm^{-2} .

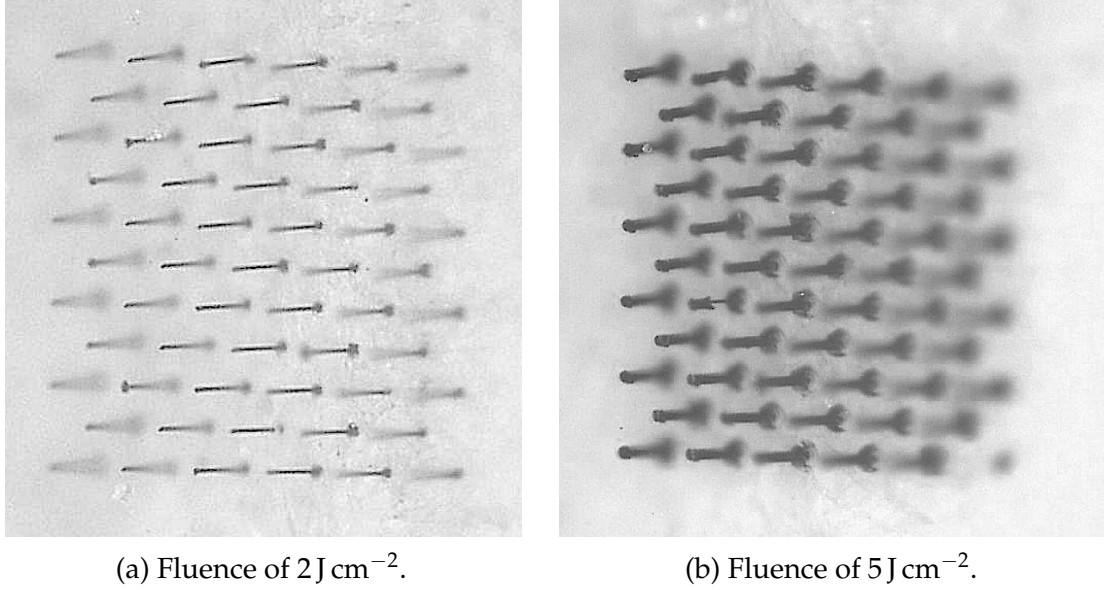


Figure 5.6: Column formation within the diamond bulk for a) the lowest and b) highest beam fluence. Since diamond is transparent, on tilting the plate $\sim 30^\circ$ to the horizontal, the dark columns are clearly visible. With a higher beam fluence larger diameter columns are formed.

source set-up. The β -emitting ^{90}Sr isotope, in combination with its daughter nucleus ^{90}Y , provides a continuous electron energy spectrum up to $\sim 2.2 \text{ MeV}$. Electrons above $\sim 1 \text{ MeV}$ can be considered MIPs and will travel several mm through diamond. Hence in requiring events to trigger a scintillator detector placed behind the diamond, the exclusive selection of MIP events was ensured. A MIP travelling through diamond produces $\sim 36 \text{ } e-h$ pairs per μm , therefore a charge of $36 \times 440 = 15840 \text{ } e$ would be expected. Previous measurements have shown maximum charge collection with electric field strengths of $>1 \text{ V } \mu\text{m}^{-1}$ [89]. With an applied bias of 500 V a charge distribution with peak value at $(15770 \pm 600) \text{ } e$ was measured, confirming the diamond was collecting full charge.

5.6.2 Laser processing

Using the optimised laser parameters: a beam fluence of 2 J cm^{-2} and translational speed of $20 \mu\text{m s}^{-1}$, an array of electrodes were fabricated into the diamond. These formed a matrix of 9×11 quadratic cells each of size $150 \mu\text{m} \times 150 \mu\text{m}$. Each cell had a read-out electrode at its centre surrounded by four bias electrodes, one in each of the cell's corners, a total of 219 electrodes. Under optical inspection the yield was measured to be in agreement with the expected $\sim 90 \%$.

Resistivity measurements were performed on a subset of the electrodes, using a probe station set-up, and are shown in Figure 5.7. The distribution peaks at $45 \text{ k}\Omega$ with a FWHM of $32 \text{ k}\Omega$. From scanning-electron-microscope measure-

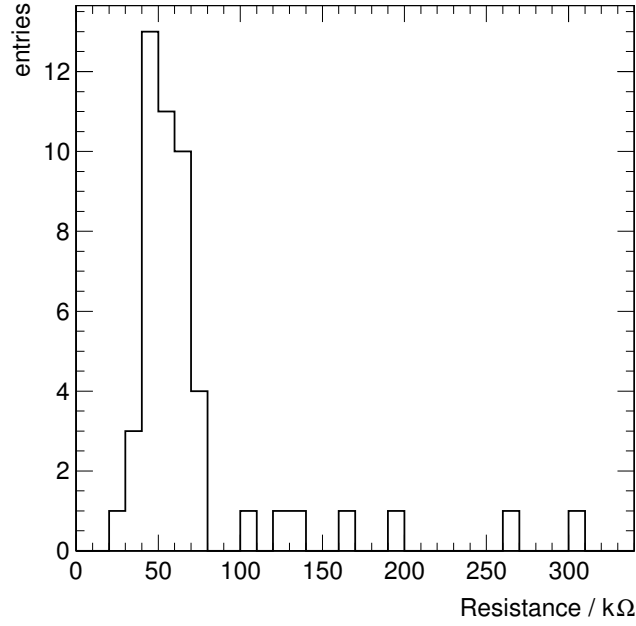


Figure 5.7: Measurements of column resistance, the distribution peaks around 45 kΩ with FWHM of 32 kΩ.

ments, the electrode diameter was estimated to be $(6 \pm 1) \mu\text{m}$. This results in a resistivity of $(0.3 \pm 0.1) \Omega \text{ cm}$ for a typical electrode. By comparison, diamond has a resistivity of $10^{14} \Omega \text{ cm}$ and graphite a resistivity of $10^{-4} \Omega \text{ cm}$, confirming that the ohmic-material formed was a mixture of the two phases. Other work has reported similar measurements of resistivity for photo induced amorphous structures in diamond [94].

5.6.3 Metallisation

To allow for electrical connections to the electrodes, a structured metallisation was formed using a photo-lithographic process with mask and sputtering deposition. In total three layers of metal were applied: titanium, platinum and gold, followed by annealing to assure a good ohmic contact to the columns and adhesion to the diamond. The metallisation was applied to the ‘entrance’ surface with regards to electrode fabrication, as the protrusion of ohmic-material increased the likelihood of a good metal-electrode contact (c.f. Figure 5.4 a). In addition to the 3D detector region, two control regions were formed, as can be seen from the lay-out in Figure 5.8:

1. A conventional planar strip detector with pitch width of $50 \mu\text{m}$.
2. A ‘phantom’ 3D detector with identical surface metallisation to the 3D detector, but with no electrodes beneath. This allowed for an estimation of the signal pick-up from the surface metallisation alone.

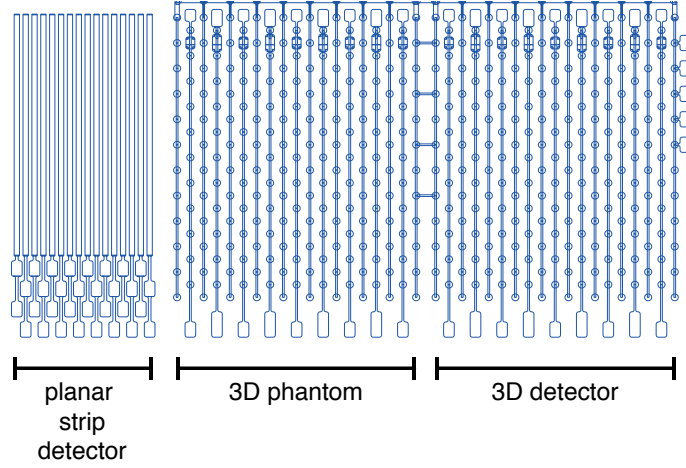


Figure 5.8: Metallisation pattern used for the prototype production.

For simplicity, the read-out structure of the 3D detector mirrored that of the planar. For each of the 9 columns of 11 cells, a single strip ganged together the cells' read-out electrodes. All bias electrodes were ganged together. This resulted in 9 strips for read-out, and 1 common bias.

5.6.4 Read-out electronics

A VA2 low-noise CMOS amplifier, was used for read-out [95]. It consisted of 128 separate channels, each with charge sensitive pre-amplifier, shaper and 'sample-and-hold circuitry'. The three detector regions were wire-bonded to three separate sections of a single VA2. A total of 16, 9 and 9 channels were used for the planar, 3D phantom and 3D detectors respectively, with several floating channels separating each section. Figure 5.9 shows the prototype after bonding.

5.7 Beam test

After fabrication, the prototype's performance was analysed in a beam test, conducted at CERN in the SPS H6 experimental area [96]. At that time, the H6 beam consisted of 'pure' hadrons of energy 120 GeV. A 'particle telescope' tracked the passage of particles through the sample, and any ionisation charge was collected and recorded by a data acquisition set-up. From the data collected, the signal spectrum of the prototype 3D detector was analysed and compared to the two control regions. Note, before any data taking was conducted, the diamond detector was 'primed' (c.f. Section 5.3.1) for four hours using a ^{90}Sr source, to ensure a consistent signal measurement throughout the beam test.

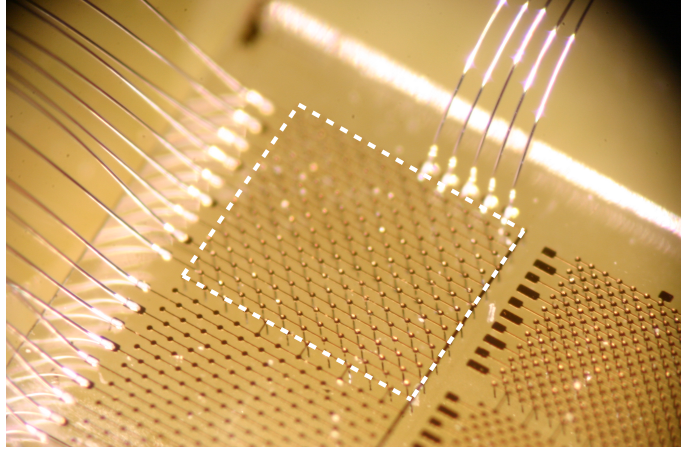


Figure 5.9: A photograph of the prototype detector bonded to the multi-channel read-out chip with the location of the $150\text{ }\mu\text{m}$ cell size 3D detector with electrodes highlighted by the dashed white frame. The read-out chip was connected via several bond-wires on the left of the image. The HV bias was supplied by the five bond-wires visible at the top-right.

5.7.1 The particle telescope

A sub-micron precision (particle) telescope, built by the University of Strasbourg, was used to track particle passage [97]. It consisted of several planes of silicon strip detectors surrounding the diamond sample under test. A traversing particle recorded a hit in each telescope plane, to which a straight line track could be fit using off-line analysis software. Through extrapolation, the position at which the track, and therefore approximately the particle, passed through the diamond could be deduced, with a previously determined extrapolation error of $0.7\text{ }\mu\text{m}$ [97]. For the purposes of track fitting a Cartesian coordinate system was used, with the z axis chosen to be parallel to the beam direction, x axis in the horizontal and y axis in the vertical directions. Rotations in the xy -plane were given in ϕ and xz -plane in θ .

Figure 5.10 shows a schematic representation of the telescope set-up. The diamond sample was placed at the centre, in one of the two available slots, and fixed in place using a fixing screw and alignment pin to reduce rotations in θ . Positioned on either side were two planes of silicon strip detectors, each plane containing one detector with strip orientation in x and another with strip orientation in y . Across the length of the telescope these provided a total of four combined ' xy ' coordinates for track fitting. Each strip detector had a pitch width of $50\text{ }\mu\text{m}$. Two external scintillators, one placed either end of the telescope and connected to a photo multiplier tube provided an event trigger. They defined an active area of $7\text{ mm} \times 7\text{ mm}$ in the xy -plane.

Each of the telescope detector planes was wire-bonded to a VA2 chip, identi-

cal to that used for the diamond sample. On receiving a coincidence trigger from the scintillators (both firing within $< 1 \mu\text{s}$ of each other), the five VA2s, four telescope and one diamond, were read-out in parallel. First an on board multiplexer placed each channel's peak voltage serially into the VA2 output buffer – with an acquisition rate of 1 MHz, the 128 channels were read-out in $128 \mu\text{s}$ – before five Siroccos (Silicon strip Read Out Camac Controllers) read-out the buffers in synchronisation, converting the signal from analogue to digital [98]. Finally, the data was saved to disk via a CPU.

The intensity of the beam was optimised for recording single hits in each of the telescope planes, within the $2 \mu\text{s}$ shaping time of the VA2 chip, in order to suppress multi-track events. Per 7 s beam spill 10 000 to 50 000 coincidence triggers were recorded in the scintillators, depending on beam conditions, from which 3600 events were saved via the data acquisition system.

5.8 Beam test analysis

The task of calculating each VA2 channel's pedestal and noise values, selecting valid signal by way of cluster finding, calculating hit coordinates, track fitting and finally alignment was achieved using off-line software. This had previously been written by students at the Swiss Federal Institute of Technology (ETHZ), and used by the RD42 Collaboration, but only on planar diamond detectors. The code had to be adapted to work with 3D detectors. The following sections describe the codes main features, the analysis steps, and the final performance of the 3D diamond prototype.

5.8.1 Pedestal analysis

When connected to a detector, the charge measured on each VA2 channel is made up of four contributions:

Physical charge, I : the charge ionised by an incident particle and the quantity we hope to measure.

Random charge, R : the 'electronic noise' in the detector.

VA2 pedestal, P : the value around which the random charge fluctuates in the absence of physical charge.

VA2 common mode noise, C : All channels are multiplexed to a single output. At the time of read-out, fluctuations on this output are common to all channels.

With the above definitions, for a particular event n , the measured charge on channel k , $Q_k(n)$, is expressed by:

$$Q_k(n) = I_k(n) + R_k(n) + P_k(n) + C(n) \quad (5.1)$$

It is possible to determine an average value for the pedestal over N events $P_k(N)$, given by:

$$P_k(N) = \frac{1}{N} \sum_{n=1}^N [Q_k(n) - I_k(n)] \quad (5.2)$$

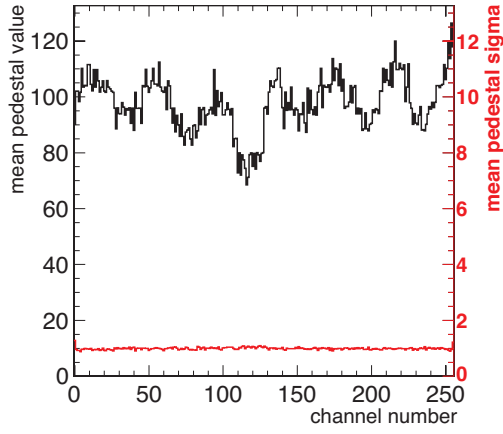
A sliding window algorithm is used to sum and average over 500 signal suppressed events, continuously updating the pedestal value for each channel [99]. Figure 5.11 shows the mean pedestal values for a) the 256 (2×128) channels connected to one of the telescope silicon planes, and b) the 34 ($16 + 9 + 9$) channels connected to the diamond sample. The error on the mean pedestal value, σ_{P_k} , is also shown. In the case of the diamond sample, the three sections connected to the planar strip, phantom 3D and 3D detector regions are clearly visible due to their non zero pedestal values. Once $P_k(n)$ has been determined, it is possible to calculate $C(n)$, common to all 128 channels on a VA2 chip, given by:

$$C(n) = \frac{1}{128} \sum_{k=1}^{k=128} [Q_k(n) - P_k(n)] \quad (5.3)$$

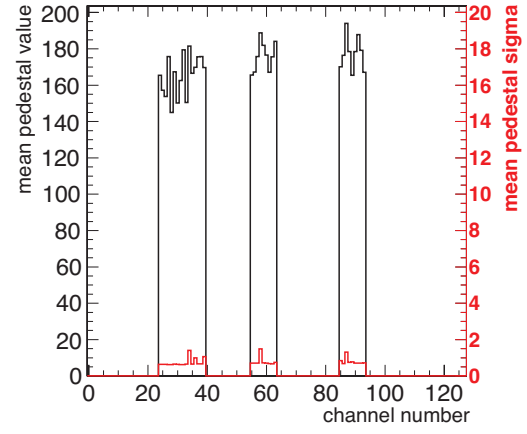
When calculating the common mode noise, in order to suppress any unwanted signal charge, channels with $(Q_k(n) - P_k(n)) > 3 \sigma_{P_k}$ are not included. Finally, the average electronic noise is determined. For the diamond sample, having averaged over all channels and events, this is measured to be $109 e$. After common mode correction, this reduces to $91 e$. Figure 5.12 shows the electronic noise, before and after common mode correction, for the three detectors on the diamond sample.

5.8.2 Cluster formation

To distinguish between charge ionised by incident particles, ‘signal’, and that of random fluctuations, ‘noise’, a threshold cut is applied. This is set at a value of $5 \times \sigma$, where σ is the common mode corrected electronic noise. For each event a hit finding algorithm scans through each channel seeking those with charge (having subtracted the pedestal) greater than the threshold value. It is common, particularly in planar detectors, for charge ionised by a particle to be shared across several channels. Hence having located a signal ‘seed’ channel, any adjoining channels with charge greater than $3 \times \sigma$ are also considered signal, thereby forming a

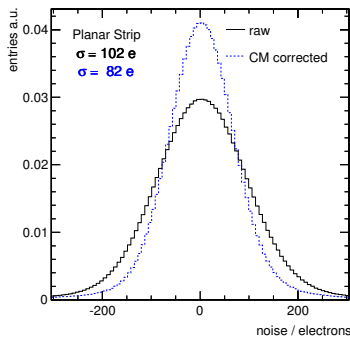


(a) Telescope silicon plane.

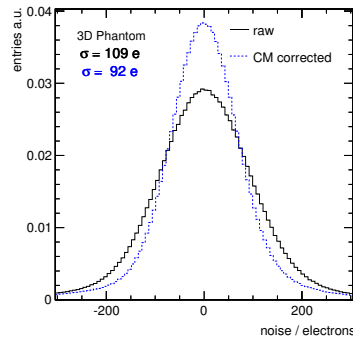


(b) Diamond sample.

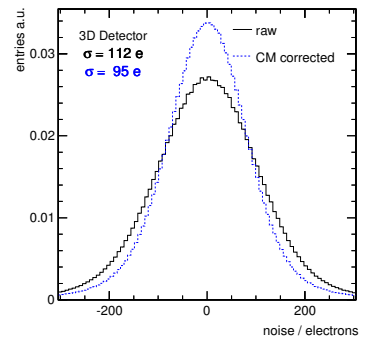
Figure 5.11: Mean pedestal values (black) and their associated errors (red).



(a) Planar strip detector.



(b) 3D phantom.



(c) 3D detector.

Figure 5.12: Electronic noise, before and after common mode correction, corresponding to 'raw' and 'CM corrected' respectively, for the three detectors on the diamond sample.

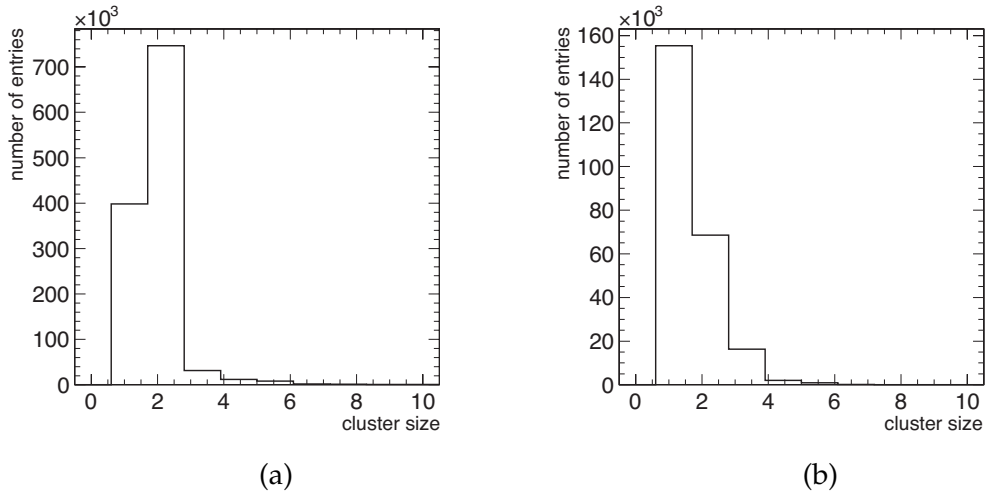


Figure 5.13: Number of channels included in a cluster for a) one of the telescope silicon detectors and b) the diamond sample.

‘cluster’ of signal channels. The total signal charge (cluster charge) is determined as the charge sum over all read-out channels contained within the cluster. Additional clusters maybe formed in the same event, for the same detector, in seeking a new seed channel with adjoining ‘ 3σ ’ channels, provided they are not included in, or adjacent to any previous clusters. Figure 5.13 compares the number of channels contained within each cluster formed in a) a telescope silicon detector and b) the diamond sample.

5.8.3 Hit position

The impact point of a particle on a detector is known as the hit position, u_h . For a strip detector, this is measured in a direction perpendicular to the strip orientation. It can be determined using a ‘digital’ or ‘centre-of-gravity’ hit finding method, as defined below:

Digital: returning the central position of the cluster’s seed channel.

Centre-of-gravity: returning a position based on the division of charge between channels in the cluster.

The centre-of-gravity method is only effective when there is a reasonable amount of charge sharing between channels. To determine whether or not this is the case, an ‘eta’ (η) distribution is made. This takes, for each cluster, the channel with highest signal charge, and the adjacent channel with higher signal charge, and compares the two. For consistency, these are labelled left and right dependent

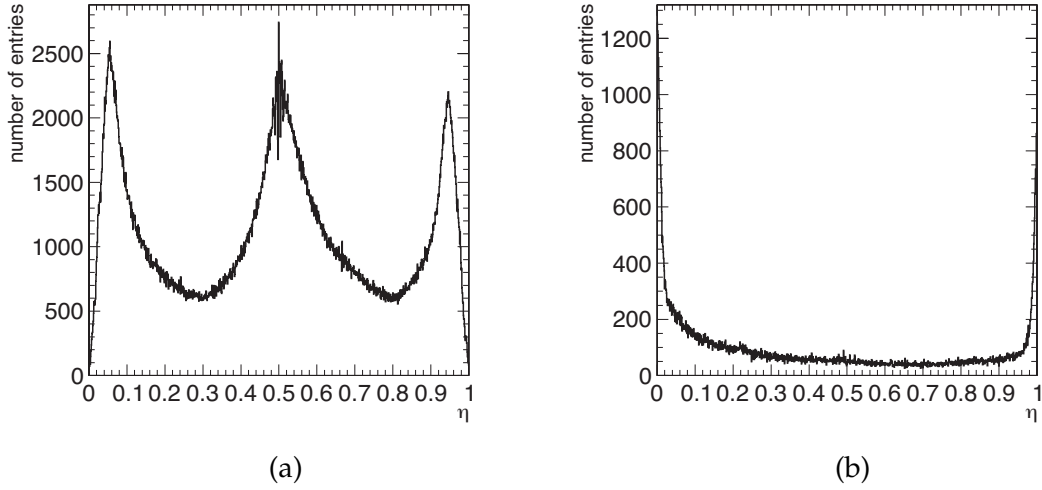


Figure 5.14: Eta distributions for a) one of the telescope silicon detectors and b) the diamond sample planar strip detector.

on the channel ordering, with the lower channel always being labelled left. The value η is then defined as:

$$\eta = \frac{Q_r}{Q_l + Q_r} \quad (5.4)$$

where Q_l and Q_r are the signal charge on the left and right channels respectively. Figure 5.14 compares the η distribution for a) one of the telescope silicon detectors, and b) the diamond sample planar strip detector. There is a small directional bias, pulling to the left, caused by the direction of read-out by the VA2 multiplexer. Even so, clearly more charge sharing occurs in the silicon detector. This is helped by the presence of a floating strip in-between each read-out strip, causing the peak at $\eta = 0.5$. As such, the centre-of-gravity hit finding method is used for the telescope detectors. In the diamond, due to the comparatively little charge sharing, the digital hit finding method is used.

Both the choice of hit finding method and amount of electronic noise affect the uncertainty on the hit position, Δu_h . This corresponds to the resolution of the detector and is measured in comparing u_h to that predicted from the telescope, u_t . In doing so, first any hit measurement from the detector in question is excluded, before a track is fitted to all other telescope planes and extrapolated back to determine u_t . Then $\Delta u_h = u_h - u_t$.

5.8.4 Telescope alignment

To simplify the alignment procedure, only single particle tracks are used. These are events with exactly one hit cluster in each telescope detector and the diamond

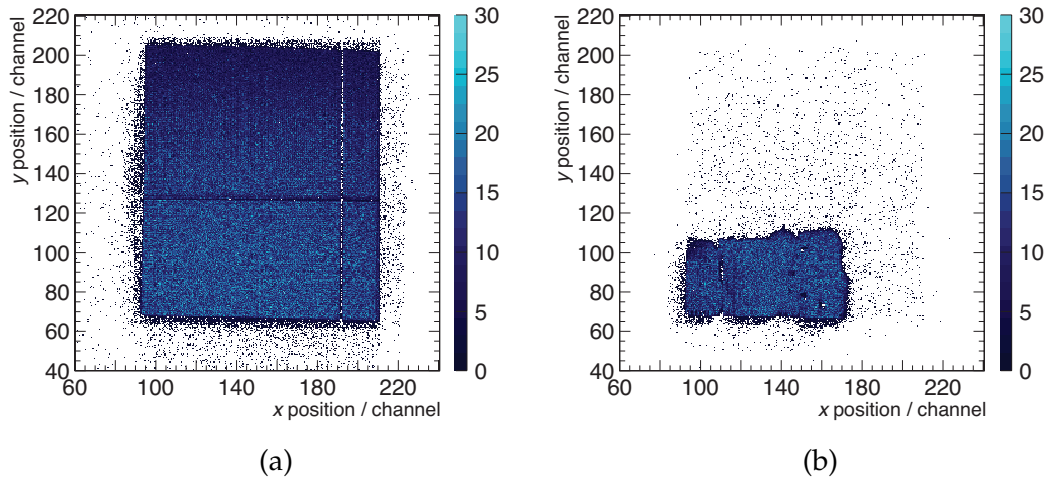


Figure 5.15: The average hit channel for a) all events with single particle tracks in the silicon telescope and b) those with an additional hit in the diamond sample. In requiring the latter, the three detector regions on the diamond sample become visible.

sample. Previously the code had been designed to work with planar strip detectors. For this reason, in addition to the single track requirement, events have to pass through the planar strip detector region on the diamond sample to be used for alignment. This also ensures an unbiased analysis of the 3D detector, in particular with regards to a measurement of its resolution.

Initially, to reduce the number of events requiring track fitting, the hit position is predicted into the diamond plane using the average hit channel (cluster seed channel) across the four telescope detector planes. Figure 5.15 a) shows this for all single particle tracks in the silicon telescope, with approximately all events falling in the active area of the two scintillators. In requiring an additional hit in the diamond sample, the three detector regions become visible, as can be seen in Figure 5.15 b). A final set of events, those falling into a fiducial region surrounding the planar strip detector, are used for alignment. Straight line tracks are fit, then a predicted and measured hit position determined for each detector plane. Figure 5.16 shows Δu_h before alignment for one of the telescope silicon detectors. One can see a significant peak in the right of the distribution, gravitating around a value of -120 . This is due to the preferential selection of events in a region on the detector, having applied the fiducial cut around the diamond sample's planar strip detector. A description of how the code determines each detector's rotation in ϕ and translation in x and y is given in [99].

Figure 5.17 compares the residual distributions after alignment for one of the telescope silicon detectors and the diamond sample planar strip detector. The latter has a digital resolution and is fitted with a boxcar convoluted with a Gaussian

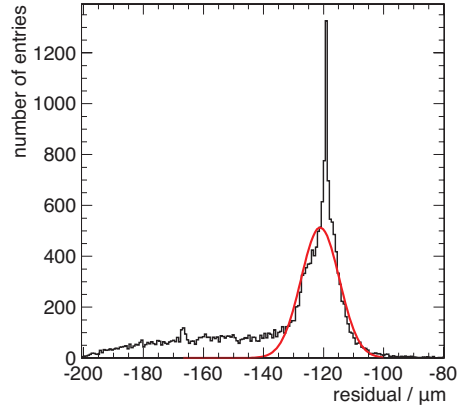
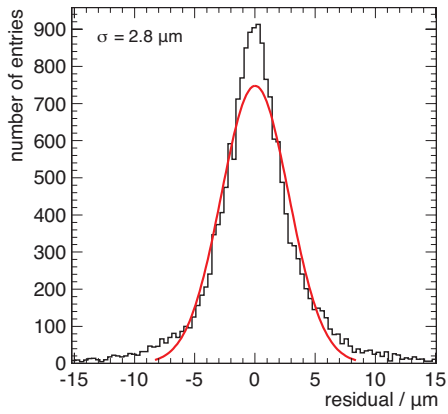
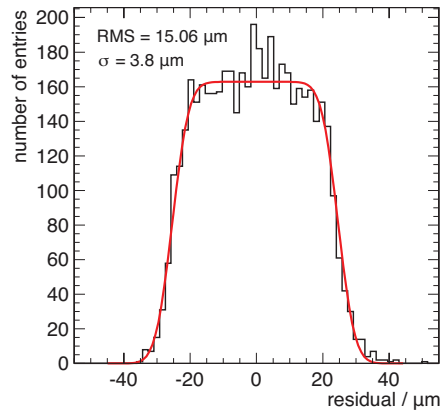


Figure 5.16: The x residual measured before alignment for one of the telescope silicon detectors. The corresponding distribution after alignment is shown in Figure 5.17 a).



(a)



(b)

Figure 5.17: The measured x residuals after alignment for a) one of the telescope silicon detectors and b) the diamond sample planar strip detector.

function with $\sigma(x) = 3.8 \pm 0.2 \mu\text{m}$.

The four planes of the silicon telescope can measure hit positions in x and y . Whereas, the diamond sample can only measure a hit position in x . Therefore the alignment method described in [99] can only be used to align the diamond sample in the x direction. An alternative method has to be established for an alignment in y .

5.8.5 Alignment in y

Having aligned the telescope silicon planes in x , y and ϕ , and the diamond sample in x and ϕ , the average cluster charge in the diamond sample as a function of predicted hit position is shown in Figure 5.18. There is an unknown offset in y . From the metallisation mask, the edges of the three detector regions are known to a high precision, and are marked with six black lines. In taking a region (a), it is possible to measure the charge distribution at the x edge of the 3D detector. This is shown in Figure 5.19 a), where this time the detector edge is marked with a red line. Clearly it coincides with a 'kink' in the distribution. In taking an equivalent region (b) for the y edge, and measuring the position of the 'kink' (c.f. Figure 5.19 b), it is possible to determine an approximate value for the y offset.

This can be improved in using cells with a defective read-out electrode. These, as shown later, collect a lower charge compared to fully functioning cells. For the region surrounding a defective cell, marked as (c) in Figure 5.18, the average charge distribution in y is shown in Figure 5.20. The distribution falls at the upper and lower edges of the cell. In optimising the upper and lower edge fit for several cells of this type, a more accurate measurement of the y offset is obtained. The final alignment step uses tracks that pass through each cell's bias and read-out electrodes, and shall be discussed later. The progressive use of these three steps results in a final alignment precision equivalent to that in x .

5.8.6 Charge spectra

From here onwards the analysis shall focus on comparing the performance, with regards to signal (charge) spectra, between the two control regions and the 3D detector region on the diamond sample. Having successfully aligned both the telescope and diamond sample, the event selection is redefined. Single particle tracks are fit to the the four telescope planes. If a hit is predicted into any one of the three detector regions on the diamond sample, the event is considered for further analysis.³

³As defined by the metallisation pattern (c.f. Section 5.8).

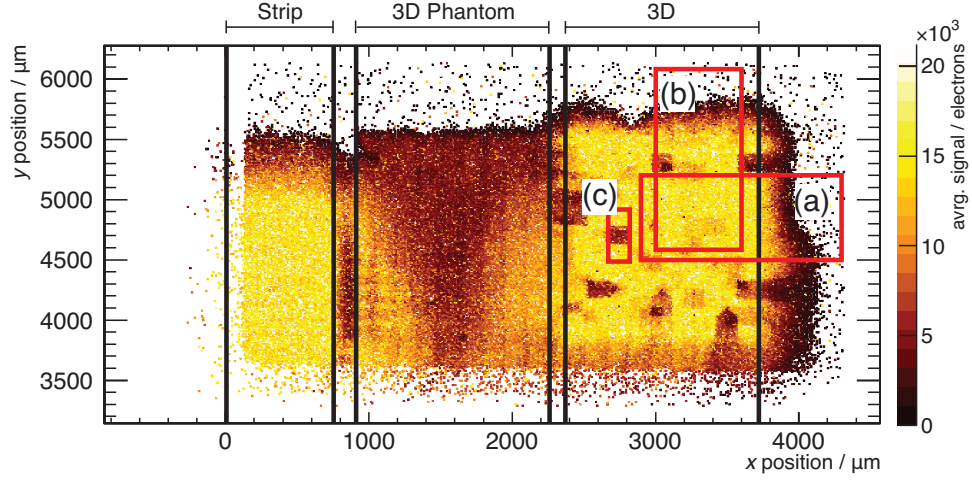
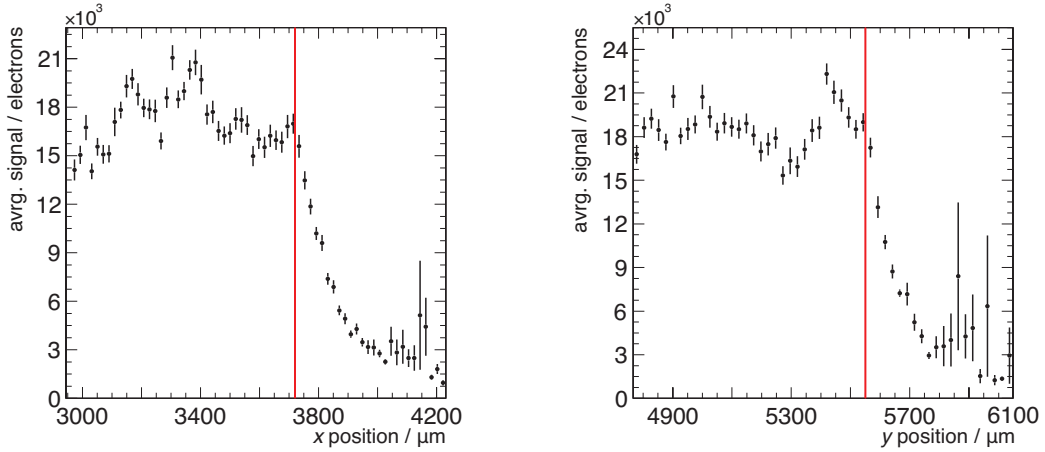


Figure 5.18: The average cluster charge in the diamond sample as a function of predicted hit position. The diamond sample has been aligned in x and ϕ but not y . Detector edges are highlighted in the x -direction. Three regions (a), (b) and (c) are used to measure the 3D detector's x , y edge-charge distributions, and the charge distribution of a cell with defective read-out electrode respectively.



(a) The x edge average charge distribution. (b) The y edge average charge distribution.

Figure 5.19: Edge-charge distributions as taken from the highlighted regions (a) and (b) in Figure 5.18. After an alignment in x , the red line marks the position of the x edge, as measured from the metallisation mask. The equivalent line in Figure b) is chosen to mirror that in a) and is positioned at the 'kink' in the distribution.

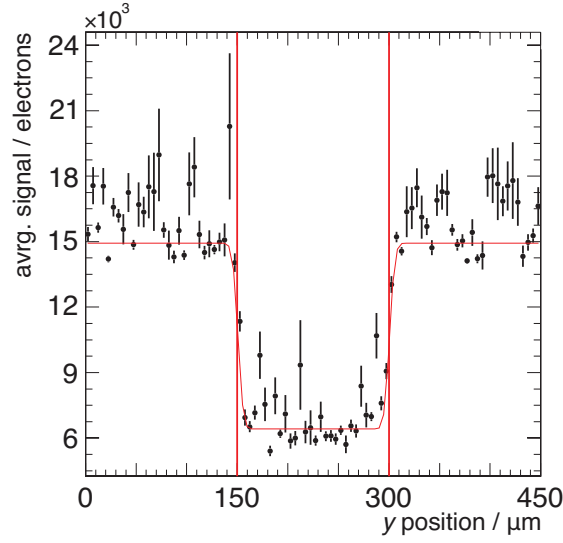


Figure 5.20: The average charge distribution in y for a cell with defective read-out electrode bordered by two fully functional cells. The upper and lower cell edges, separated by $150\text{ }\mu\text{m}$, are marked with a red line. An equivalent distribution is made for other cells with defective read-out electrode. In optimising the upper and lower edge fit for several cells of this type, the y alignment is improved.

First, the cluster forming algorithm, as defined in Section 5.8.2, scans through all channels on the diamond sample VA2, constructing hit clusters. In doing so, there is the potential for multiple clusters to be formed in more than one region. Since a strict selection on single particle tracks is applied when track fitting to the four telescope planes, if a significant amount of multiple clusters are observed, it may highlight regions of electric field distortion or signal pick-up between detectors. Usually the use of guard rings would help prevent this, however, in the design of the diamond prototype no guard rings were included. Figure 5.21 compares the predicted hit position on the diamond sample for events containing exactly one cluster (green) and those containing greater than one cluster (blue), with the three detector regions outlined and labelled. Clearly a significant number of multi-cluster events occur when tracks are predicted into the right half of the 3D phantom detector. Later these shall be removed from the analysis. For now, the signal charge in events of this type is calculated from the sum of charge contained within the multiple clusters formed.

Bearing this in mind, the average signal charge as a function of predicted impact point on the diamond is shown in Figure 5.22. The planar strip detector extends past the geometrical acceptance region of the trigger scintillators. Only the strips in the trigger shadow are included in the analysis that follows. The signal distortion observed between the 3D phantom and 3D detectors is now mirrored between the 3D phantom and planar strip detector.

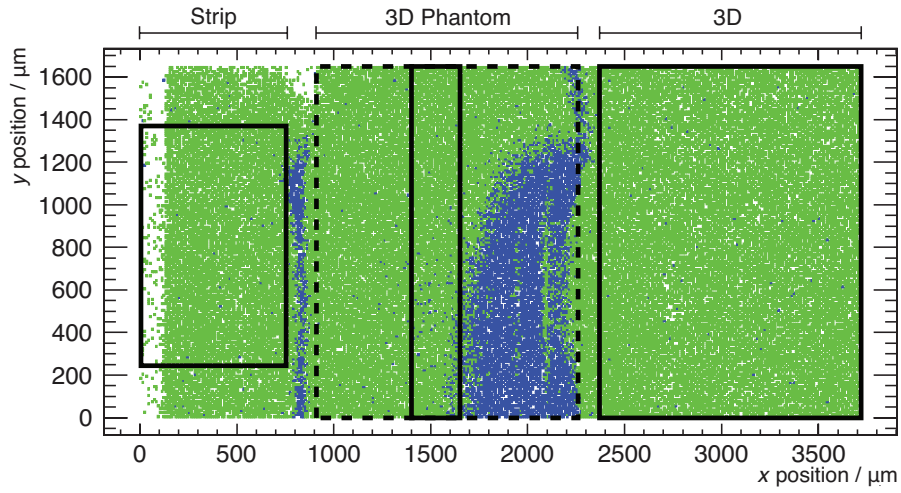


Figure 5.21: Predicted track positions in the diamond sample for events with exactly one cluster (green), and those with greater than one cluster (blue).

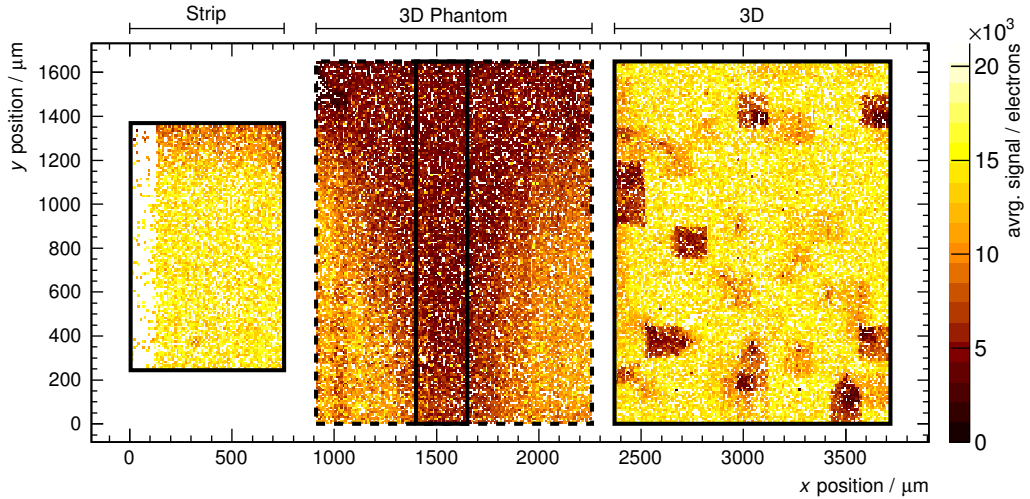


Figure 5.22: The average signal charge of the prototype detector as a function of the predicted track position. In this plot the signal charge is defined as the sum over all charge contained within a cluster/clusters for an event. The planar strip, 3D phantom and 3D detector regions are outlined.

5.8.7 Transparent cluster

To ensure an unbiased analysis of the signal charge spectra, a new cluster finding algorithm is defined. This takes the predicted impact point on the diamond sample and builds a ‘transparent’ cluster from the three closest channels. In this way there is no threshold cut placed on a channel’s charge for it to be included in a cluster. By definition it is only possible for events to contain a single transparent cluster, due to the single track requirement. The remainder of this analysis exclusively makes use of transparent clusters, therefore, from here on, whenever clusters are referred to they are assumed to be transparent unless otherwise stated.

The cluster charge spectra obtained from the three detector regions are shown in Figures 5.23 and 5.24, having been scaled to the same peak height. The cluster charge of the planar strip detector exhibits a typical Landau distribution, with a most probable value around $\sim 13700 e$ [100]. The 3D detector shows a more complex distribution, consisting of an upper peak around $\sim 13500 e$ and a lower peak around $\sim 6600 e$. The upper peak roughly coincides with the most probable value of the planar strip detector.

In Figure 5.24 the cluster charge spectra obtained from the entire 3D phantom detector (dotted) and only its central region (dashed) are shown. The central region exhibits a Landau shape, with a most probable value at $\sim 4450 e$, considerably lower than the planar strip and 3D detectors. This is expected, since the 3D phantom detector is essentially an inter-digitated surface device, only collecting charge near the surface.

In comparing the 3D detector and 3D phantom’s central region, any differences in charge spectra must be attributed to the presence of electrodes; with the 3D phantom detector representing the extreme failure mode of the 3D detector. Hence in the 3D detector, cells with a defective read-out column, i.e., a non-continuous, disconnected or missing column, will give a signal approaching the response of the 3D phantom detector. These defective cells are the cause of the lower secondary peak in the 3D detector spectrum.

A map of average cluster charge in the 3D detector is shown in Figure 5.25. A grid has been overlaid to show the position of cell boundaries. Each square has a read-out column at its centre and bias columns in each of the four corners. There are nine cells which show a low signal response due to defective read-out columns. This was verified by comparison to measurements of the column resistance made before the beam test. Nine defective read-out columns out of a total of 99 is consistent with the 90 % yield (c.f. Section 5.5). Since, in the fabrication process, there is no distinction between read-out and bias columns, we expect $\sim 10\%$ of the 120 bias columns to also be defective.

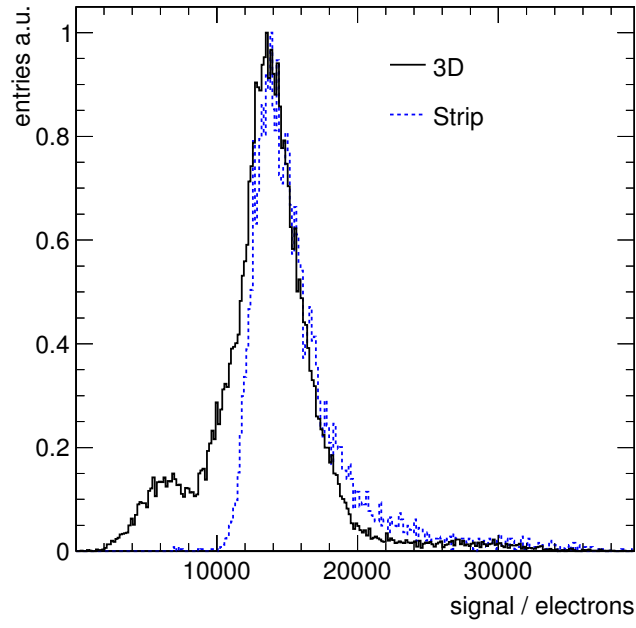


Figure 5.23: The cluster charge spectra from the strip and 3D detectors scaled to the same peak height. The strip detector has a most probable value of $13\,700\,e$, while the 3D detector has a most probable value at $13\,500\,e$.

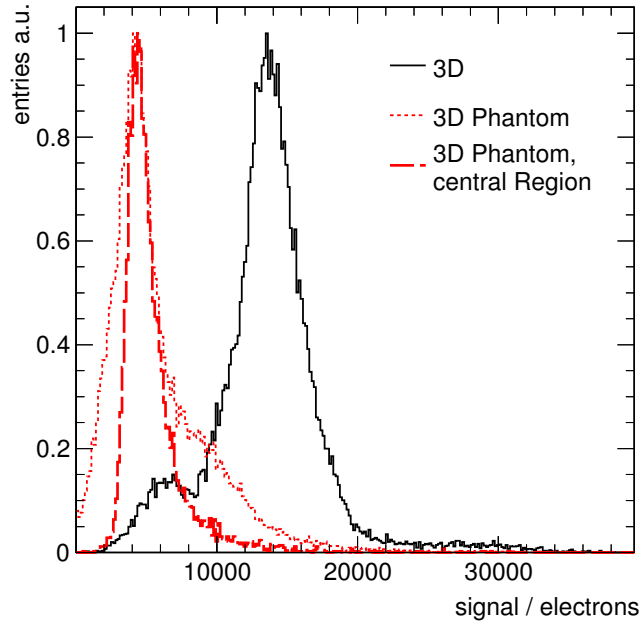


Figure 5.24: The cluster charge spectra from the 3D phantom and the 3D detector scaled to the same peak height. The 3D phantom (red-dashed) exhibits a significantly lower cluster charge spectrum with a most probable value at about $4\,450\,e$. The 3D detector (black-solid) has a most probable value at $13\,500\,e$ and features a lower secondary peak at $6\,600\,e$.

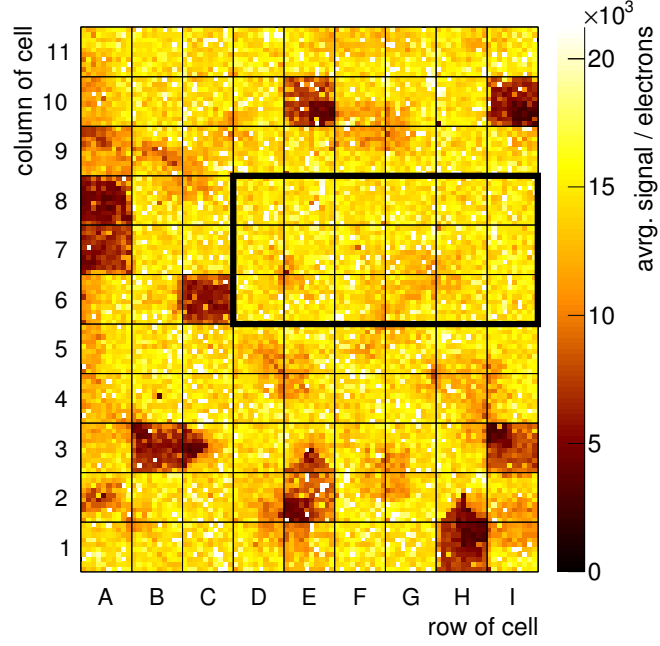


Figure 5.25: The average cluster charge versus hit position in the 3D detector. The individual cells are marked by the overlay. Each cell has a read-out column at its centre and bias columns in the corners. In total there are 99 cells referenced from A1 to I11. Cells A7, A8, B3, C6, E2, E10, H1, I3, and I10 show weak response due to defective read-out columns. A subset of adjacent cells with working read-out columns is highlighted.

5.8.8 Negative charge

In the 3D detector, around 15 % of transparent clusters are observed to contain channels with significant negative charge, less than $-700 e \cong 7.0 \alpha$. It is possible to observe due to the method used for transparent cluster formation and can not be explained by noise fluctuations. The negative charge is predominantly found in the channel second closest to the impact point, as can be seen in Figure 5.26. Figure 5.27 shows the position of these clusters in the 3D detector. Clearly they are not evenly distributed throughout the detector, and instead cluster around bias columns. This leads to the idea that defective bias columns might be causing negative charge.

The scenario is simulated using the Sentauros package, taking into account the electric field distribution, field dependent hole and electron mobilities, and finite lifetime of charge carriers [101]. Figure 5.28 shows the electric field distribution for a fully functional cell, and cell with a missing bias column. The field strength around the missing column is significantly reduced, leading to lower drift speeds of the charge carriers within this region. With a finite lifetime, the electrons and holes are trapped before they can reach an electrode. The associated weighting field leads to an induced charge with opposite sign on a neighbouring

electrode. Similar effects have been observed with 3D silicon detectors.

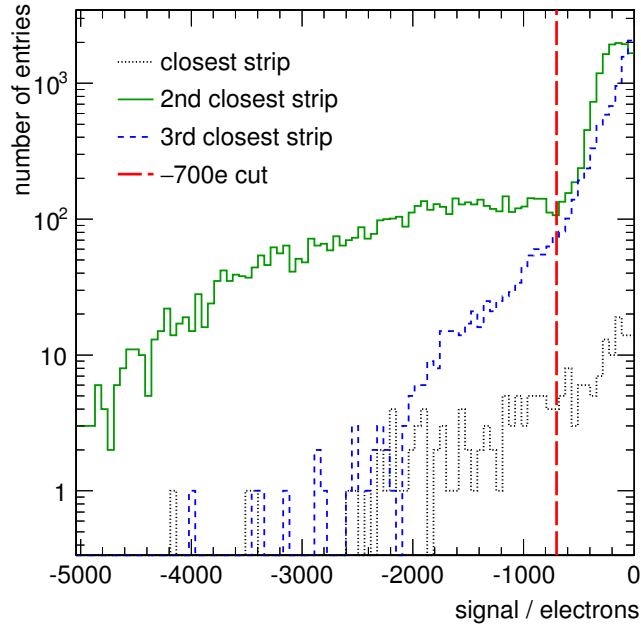


Figure 5.26: The negative charge contributions of the channels contained in the transparent clusters. The three channels are sorted by distance to the predicted track position. The cut of $-700 e$ to define a negative signal is indicated by the red vertical dashed line. After applying the cut, 88 % of all negative signals appear in the 2nd nearest strip (green solid line) to the predicted position.

When mapping the predicted position of negative charge events onto the full 3D detector, it appears that most are clustered around 20 bias columns. This is consistent with the expected failure rate and the simulation based evidence that negative charge signals are an indicator of a defective bias column.

5.8.9 3D/planar comparison

To exclude the contribution of cells with defective read-out column from the signal spectrum, a continuous region, in which there are only fully functional read-out columns, is selected on the 3D detector. This is highlighted by a rectangle in Figure 5.25. Events containing significant negative charge, i.e., below $-700 e$, are removed. Figure 5.29 shows the signal charge spectra of the selected region for the 3D detector overlaid with the spectrum from the planar strip detector. The two spectra are consistent in their most probable value. The strip detector exhibits a slightly longer tail associated with large energy transfers. This difference is currently not understood.

Using the region highlighted in Figure 5.25, the spatial resolution of the 3D detector is investigated. This is only possible in the x direction due to cells being

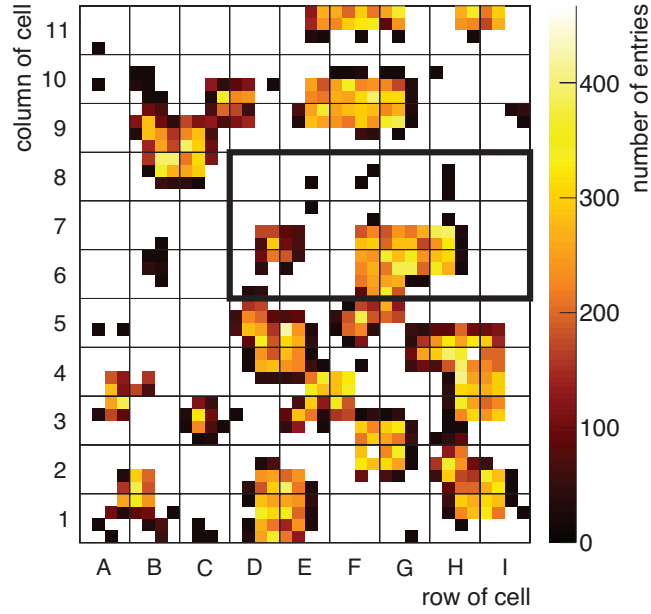


Figure 5.27: Predicted hit position within the 3D detector for all events where a negative charge below $-700 e$ has been observed. Bias lines are located at the crossing of the lines. There is a clustering of these events around bias columns. This could be an indicator for broken bias columns. The black rectangle marks a subset of adjacent cells with working read-out columns.

ganged together in y . From the η distribution shown in Figure 5.30 a), there is little charge sharing present between cells. As such, a digital hit finding method is used when determining the measured hit position u_h . Figure 5.30 b) shows the resulting Δu_h distribution, with measured resolution of $\sigma(x) = 40.2 \pm 0.3 \mu\text{m}$. Increased charge sharing and therefore an improved resolution could be achieved by tilting the detector relative to the incident particle direction. In this case, more than one cell would likely be traversed by an incident particle, and signal will be collected in both.

5.8.10 Cell analysis

Excluding the 9 3D cells with a non-functional read-out electrodes, there are on average, 235 tracks per cell. This corresponds to ~ 0.01 tracks per μm^2 , a value too low to observe any structure within the cell itself. However, since all cells are essentially identical, they can be overlaid. Having done this for the 90 remaining cells Figure 5.31 a) shows the average cluster charge as a function of hit position within the cell. The four bias electrodes are marked with black dots, and the read-out electrode with a red dot. The $150 \mu\text{m} \times 150 \mu\text{m}$ cell is split into array of 15×15 bins, each with width of $10 \mu\text{m}$. This results in approximately 94 ± 9 entries per bin. Figure 5.31 b) shows the distribution of each bin's average charge.

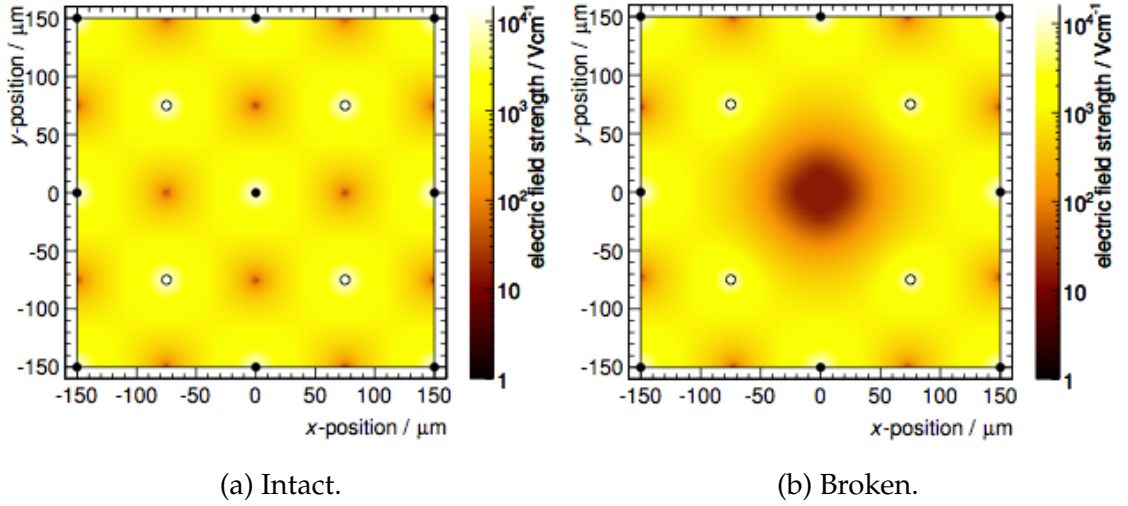


Figure 5.28: The calculated electric field strength distributions of a four cell array a) in the case of fully functional cells and b) in the case of a missing bias column, for a bias voltage of 25 V. Bias columns are marked with solid circles and read-out columns are marked with empty circles.

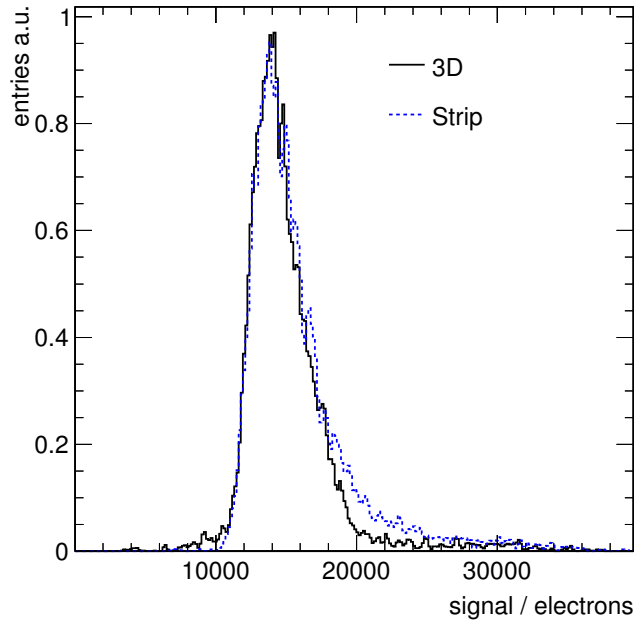


Figure 5.29: The transparent charge pulse height spectra of the strip detector and 3D detector continuous fiducial region, as highlighted in Figure 5.25. The average charge in the strip detector is $16\,800\,e$, the average charge of the 3D detector is $15\,900\,e$. The peak of the strip detector charge distribution is $\sim 14\,700\,e$, the peak of the charge distribution of the 3D detector is $\sim 15\,000\,e$.

The central bin is highlighted in red and the four corner bins in blue. Excluding these, the distribution has an RMS deviation of 3 %, indicating a uniform charge collection across the cell.

The central bin is positioned approximately 7σ below the distribution mean,

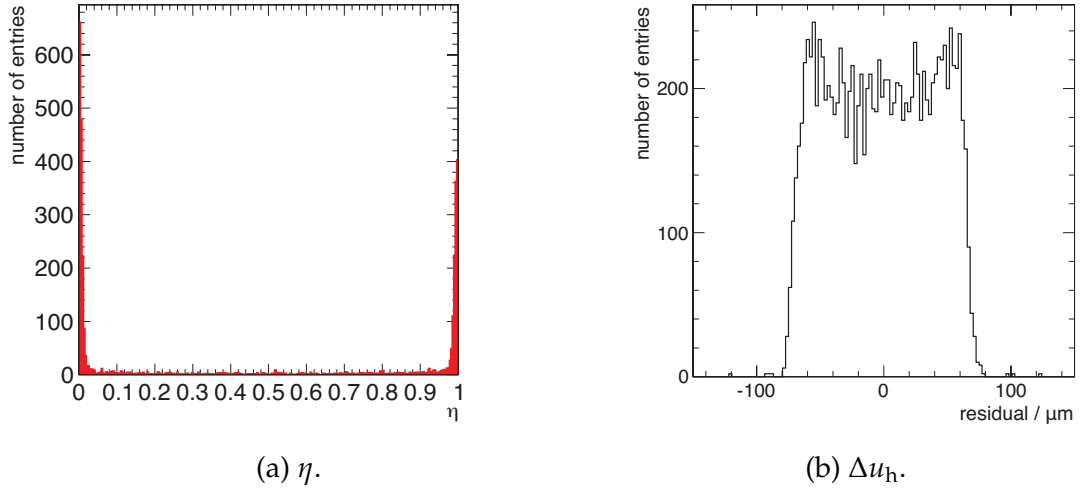


Figure 5.30: The measured η and Δu_h distributions for the 3D detector, using the continuous region highlighted in Figure 5.25.

and all corner bins are in the lower half of the distribution. Hence, the presence of an electrode clearly reduces the average charge collection within a bin. Through optical measurements electrodes are estimated to have a diameter of $\sim 6 \mu\text{m}$, therefore in a $10 \mu\text{m} \times 10 \mu\text{m}$ bin approximately 28 % of its area is covered by the electrode. Figure 5.32 compares the cluster charge spectra from the central bin to that of a bin containing no electrode. In the case of the central bin, there is a lower peak present, below $7000 e$, containing 30 % of the entries and presumably due to tracks passing through the electrode. This corroborates the view that particles traversing the electrode yield lower or no signals. The corner bins contain a quarter of an electrode, therefore, only about 7 % of events are expected to yield lower charge. As such, the effect is less significant in these bins.

5.8.11 Electrode alignment

Figure 5.33 a) shows the cell overlay after having applied a $30 \mu\text{m}$ shift in both the x and y directions. Bin segmentation remains the same as before. The read-out electrode is now located at $105 \mu\text{m}$, in both x and y , and contained within one bin, highlighted in green. Whereas the bias electrode is positioned at the centre of four bins and highlighted in red. By studying the ratio of events below $7000 e$ in each of these four bins, it is possible to confirm the accuracy of the alignment procedure, as shown in Figure 5.33 b), c) and d). A shift of $(0 \mu\text{m}, 0 \mu\text{m})$ is the initial alignment achieved by the methods discussed in Sections 5.8.4 and 5.8.5. In this case, events are evenly distributed across the four bins. With a shift of $(4 \mu\text{m}, 4 \mu\text{m})$ more are present in the top-right, whereas a shift of $(-4 \mu\text{m}, -4 \mu\text{m})$

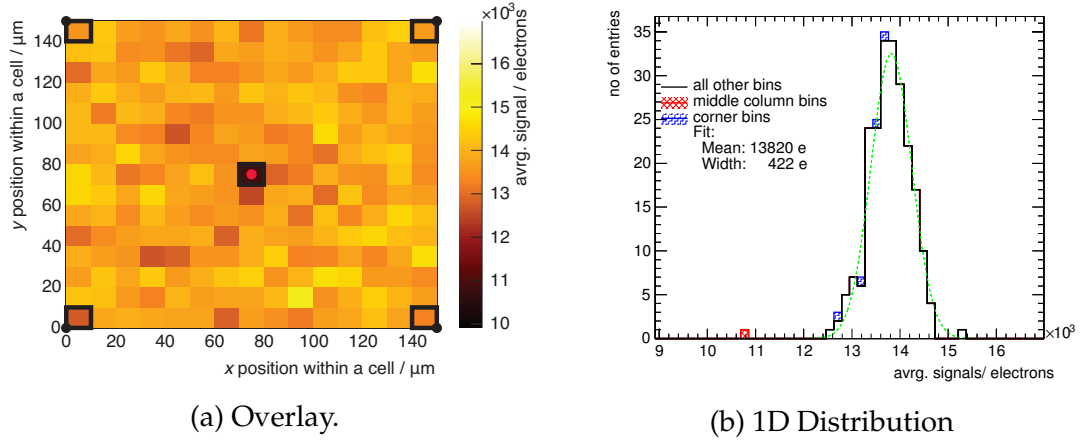


Figure 5.31: a) The average cluster charge as a function of the hit position within the cell. The dots correspond to the position of the read-out electrode (red) and the bias electrodes (black). b) shows the 1D distribution of the average bin charge, where the position of central bin (red) and four corner bins (blue) are highlighted.

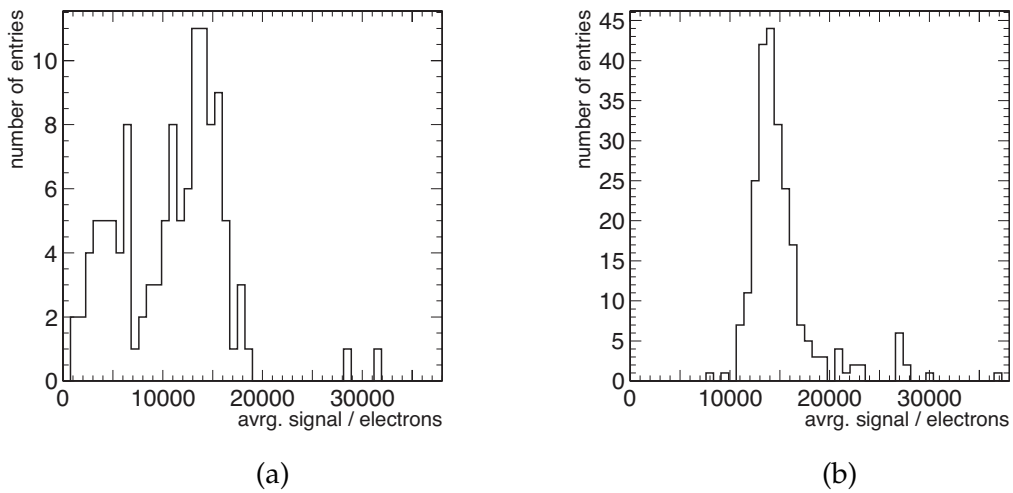


Figure 5.32: Transparent charge distributions for two bins in the 3D detector cell overlay. a) the central bin containing an electrode, and b) a bin containing no electrode. Approximately 30 % of the central bin is covered by the electrode, causing the lower peak in the distribution.

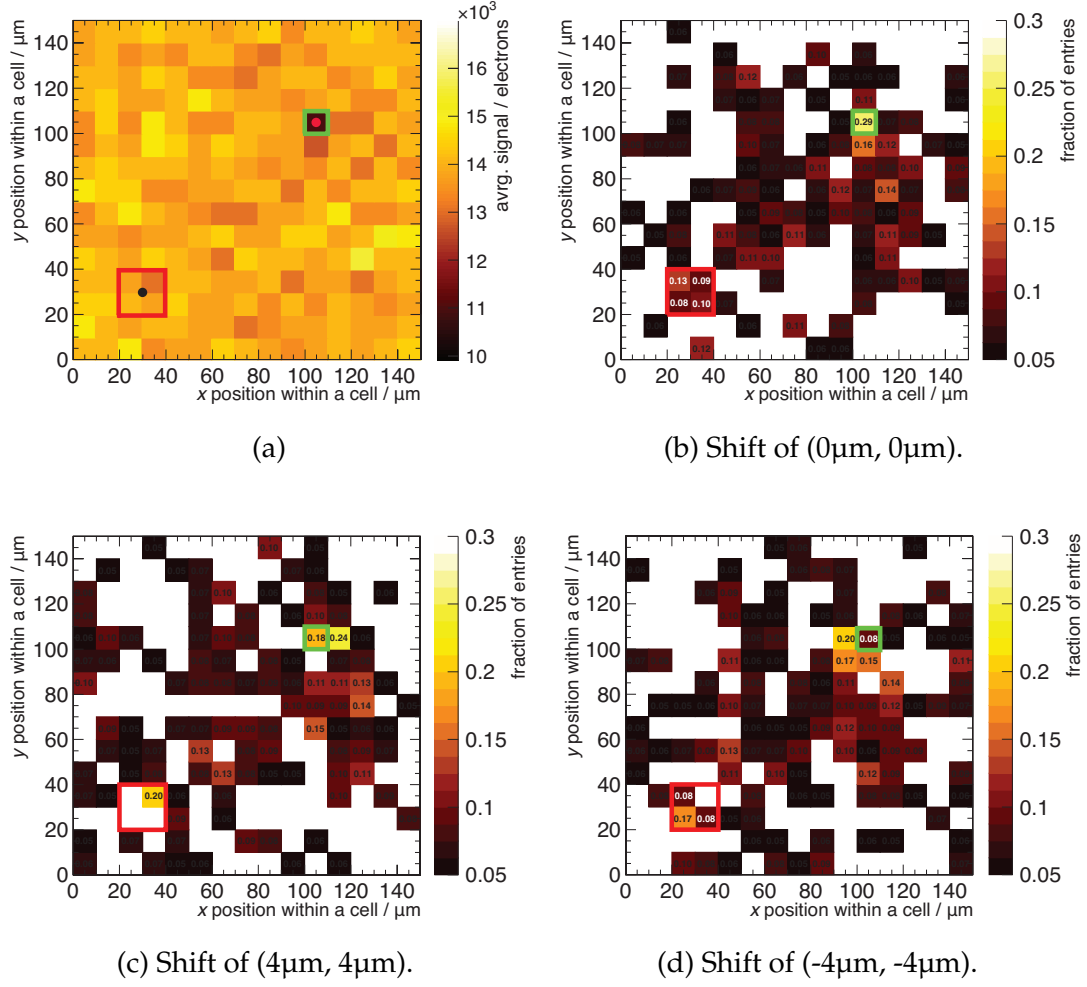


Figure 5.33: a) The average cluster charge as a function of the hit position within the cell having applied a shift of $30\mu\text{m}$ in both the x and y directions. b) shows the corresponding fraction of entries below $7000e$ in each bin. c) and d) show how the fraction of entries below $7000e$ vary with additional shifts of $(4\mu\text{m}, 4\mu\text{m})$ and $(-4\mu\text{m}, -4\mu\text{m})$ respectively. In all cases the central column bin is highlighted in green, and the four corner bins in red.

places more events below $7000e$ in the bottom-left. The observation of this trend confirms the accuracy of alignment in both the x and y directions. Even with relatively low statistics, ~ 30 electrode events, the effect is observable. Hence, in the future, with increased statistics, this might be a very powerful technique for detector alignment.

5.9 Conclusions

This chapter has detailed the development, fabrication and testing of a proof-of-principle 3D diamond detector. The starting material was chosen to be SC diamond, due to its well-understood charge collection properties. A femto-second

laser was used to form an array of ohmic-electrodes, where after optimisation a yield of 92 % for fully functioning electrodes was achieved. Once fabricated the prototype was placed in a beam of high energy 120 GeV protons. The inclusion of a reference planar strip and 3D phantom in addition to the 3D detector allowed for a conclusive demonstration of its functionality. The 3D diamond detector was shown to collect equivalent charge to the planar with $\sim 5\%$ the applied bias corresponding to $\sim 10\%$ the applied electric field. In comparison the 3D phantom only collected approximately one-third of the charge, thus proving that the electrodes in the 3D detector were collecting a further two-thirds. Investigation into the charge spectra showed that failed (incomplete or missing) read-out and bias electrodes led to regions of low signal collection and negative charge. As expected negligible charge sharing was observed between 3D cells, and a detector resolution close to the digital resolution was measured. Altogether, this work has shown the concept of a 3D diamond detector to be viable, potentially leading in a new research direction for radiation tolerant detectors.

One major benefit of the laser fabrication process is its flexibility in terms of electrode positioning and properties. This allows for rapid, low cost prototyping compared to custom patterned 3D silicon detectors, hence novel electrode geometries and/or layouts can be developed for specialised applications with very quick turn-around. However, a greater understanding of the laser process is required. The yield of fully functioning electrodes needs to be improved; their resistivity needs to be reduced, as a resistivity of $\sim 0.3\ \Omega\text{ cm}$ would likely cause problems for very fast signals; and finally the scalability of the laser process needs to be explored. In addition to this, future work shall focus on the viability of using PC diamond as substrates which are available in larger sizes than SC. If it can be proven a 3D geometry improves the charge collection properties of PC diamond, this would be a major development for their use in high energy experiments. Clearly another important step is to investigate the radiation tolerance of 3D diamond detectors, making direct comparison to planar geometries and even 3D silicon.

Chapter 6

ATLAS part II

6.1 Introduction

The ATLAS ID, with its combination of three sub-detectors detailed in Chapter 2, provides precision tracking and momentum measurements of charged particles. It allows for accurate reconstruction of primary (interaction) and secondary (decay) vertices, and can provide electron identification over a wide range of energies. Section 2.2 described how a supplementary layer of higher granularity detectors closer to the beam-line maintains the performance of the ATLAS ID with increased pileup; providing additional redundancy against module failures, improving particle tracking, and enhancing the measurement accuracy of secondary vertices.

We shall now move on from the technical work required (especially with regards to radiation damage) in placing detectors so close to the beam-line, to the potential gains in physics analysis. However, first the remainder of the ATLAS detector shall be described, from the ID outwards, which for the purposes of this thesis shall be referred to as the ‘outer-detector’. Using data taken in 2012, chapters 7 to 9, go on to discuss the feasibility of observing a very rare di-boson process involving taus in its final state, an analysis which will benefit significantly from the increase in beam-energy, luminosity, and future pixel detector upgrades.

6.2 The outer-detector

The outer-detector refers to sub-detectors beyond the ID. It includes the electromagnetic and hadronic calorimeters that measure the energy of particles, and the muon spectrometer for muon measurements. Figure 6.1 shows a cross-sectional segment of the entire ATLAS detector. It demonstrates why both the ID and outer-detector are required to fully understand the interaction of each particle

type and their associated signature. Referring to Figure 6.1, the characteristic behaviour exhibited by several simple particles would be:

Neutrino, ν : Travelling through the detector without interacting, its presence is inferred from the missing energy and momentum in a collision.

Electron, e : Due to its charge, it leaves a curved track in the tracking detector. All its energy is deposited in the EM calorimeter.

Muon, μ : With higher mass than the electron, it travels through all the detector layers, leaving tracks and energy deposits.

Proton, p : Its path is curved in the magnetic field, leaving tracks in the tracking detectors. All its energy is deposited in the electromagnetic and hadronic calorimeters.

Neutron, n : Being charge neutral, its trajectory is not effected by the magnetic field. No tracks are left in the tracking detectors. All its energy is deposited in the electromagnetic and hadronic calorimeters.

Photon, γ : As in the case of the neutron, it is charge neutral, and therefore not affected by the magnetic field. All of its energy is deposited in the EM calorimeter.

The following sections describe each of the sub-detectors that make up the outer-detector.

6.2.1 Electromagnetic calorimeter

The electromagnetic (EM) calorimeter uses alternate layers of lead and liquid argon (LAr) to measure the energy of electrons and photons. On passing through, electrons emit bremsstrahlung photons, that may themselves have enough energy to produce electron-positron pairs. The resulting shower of electromagnetic particles causes ionisation in the LAr. The ionised charge is collected by copper electrodes sandwiched in-between each lead/LAr layer. The total signal produced is proportional to the energy of the particle that initiated the shower. An energy conversion factor is determined from well understood resonances such as $Z \rightarrow ee$ [103]. The EM calorimeter follows the basic structure of the ATLAS detector with barrel and end-cap regions. An accordion-shaped geometry allows for complete coverage in ϕ without any cracks or gaps. The material thickness of both the barrel and end-caps is chosen to minimise ‘leakage’ of electrons/photons beyond the EM calorimeter. For this reason 22 to 33 radiation lengths (X_0)

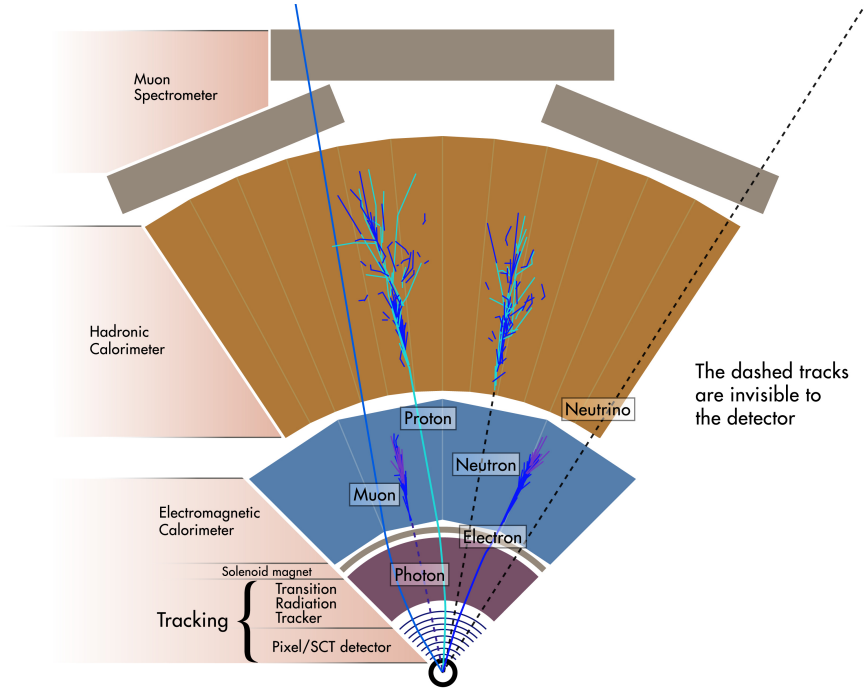


Figure 6.1: Cross-sectional segment of the ATLAS detector. The trajectories of several particles are shown, with various interactions in the inner and outer detectors. [102]

of material are present in both [104]. The EM calorimeter is split-up into cells, as shown in Figure 6.2 for a barrel segment. Three layers provide varying granularity. The second layer absorbs the majority of energy with $16 X_0$. Its granularity of 0.025×0.025 in $\eta \times \phi$ is ideally suited for precision measurements on electrons and photons. Both barrel and end-cap EM calorimeters are housed in their own cryostat, with operating temperatures of 87 K. This keeps the argon in a liquid state.¹ In the transition region between cryostats, $1.37 < |\eta| < 1.52$, the additional infrastructure effects the energy resolution. Overall, the EM calorimeter provides precision energy measurements over the range $|\eta| < 3.2$.

6.2.2 Hadronic calorimeter

Analogous to the EM calorimeter, the hadronic calorimeter uses alternate layers of material to measure the energy of baryons and mesons (particles formed from quark triplets and quark-antiquark pairs respectively). However, this time, rather than lead, steel is used to initiate particle showers, and rather than LAr, a scintillating material used to absorb the energy. The scintillating material re-emits the absorbed energy as ultraviolet light, before it is wave-shifted into the visible range by fibres that transmit the light to photomultiplier tubes (PMTs) located

¹The melting and boiling points of Argon are 83.8 K and 87.3 K respectively.

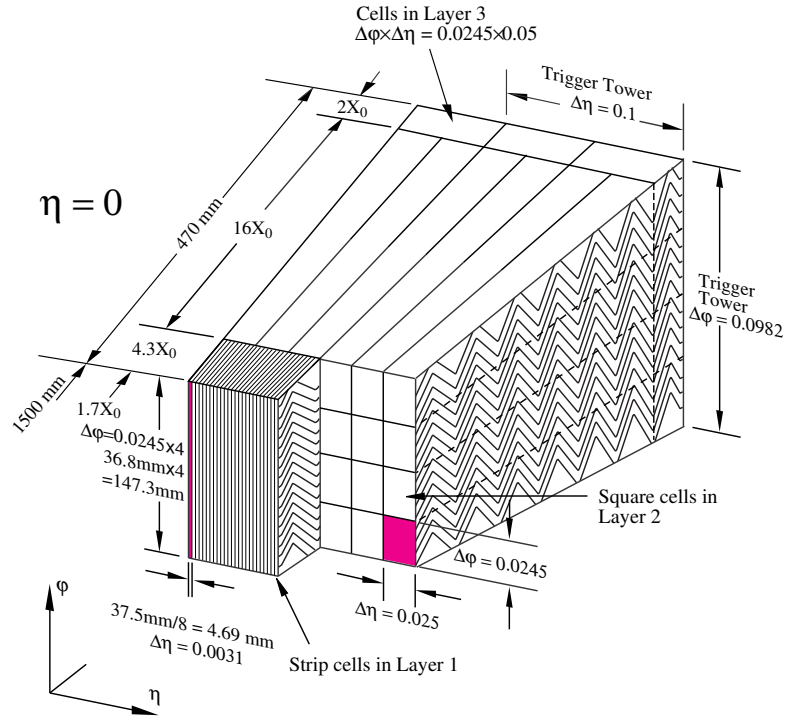


Figure 6.2: Diagram of an EM calorimeter barrel module, showing the granularity in η and ϕ of its three layers [29].

at the edge of the module. As before, the total energy absorbed is proportional to the signal measured in the PMTs. Figure 6.3 shows the design of a hadronic calorimeter module. A total of 64 modules make up the hadronic calorimeter barrel, covering the region $|\eta| < 1.7$. End-caps extend this coverage to $|\eta| < 3.5$. Varying granularity is provided in two layers, the first with cell dimensions 0.1×0.1 in $\eta \times \phi$ and second 0.2×0.1 .

6.2.3 Forward calorimeters

Forward calorimeters, placed either end of ATLAS, extend both the EM and hadronic calorimeters range to $|\eta| < 4.9$. They are designed to provide faster signals, in order to cope with the large particle flux produced at low angles with respect to the beam.

6.2.4 Muon spectrometer

Muons are approximately MIPs for the energy range in which they are produced at the LHC – they deposit minimal energy in each of the sub-detector layers (c.f. Chapter 3). As such, they are generally the only particles, other than neutrinos, likely to plough all the way to the outermost regions of the ATLAS detector. Hence the most external sub-detector system is the Muon Spectrometer (MS).

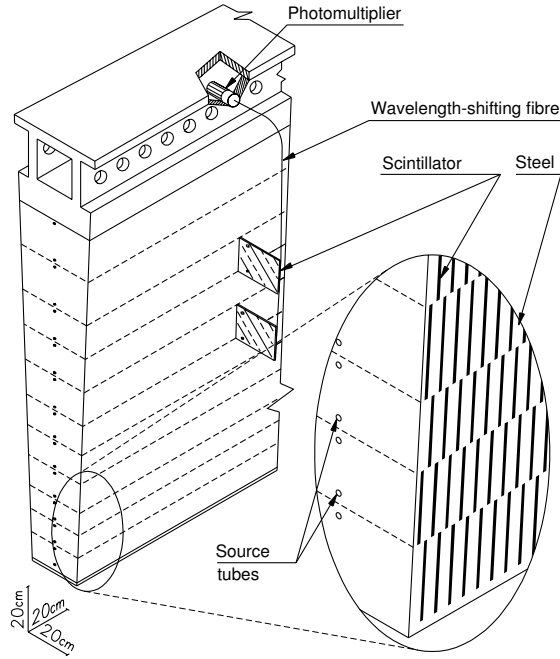


Figure 6.3: Diagram of a hadronic calorimeter tile module, showing the layout of the steel plates used to initiate particle showers and the scintillating material placed in-between [29].

The MS uses a combination of large, superconducting magnets to bend muons in a plane containing the beam, and muon chambers for detection. Eight large, rectangular loops form the barrel magnets. These provide a bending power of 1.5 T m to 5.5 T m in the pseudorapidity range $|\eta| < 1.7$. Two end-cap magnets continue the magnetic field out to larger values of η , with bending power of approximately 1 T m to 7.5 T m in the region $1.1 < |\eta| < 2.7$.²

Three layers of muon-chambers in both the barrel and end-cap detect muons up to $|\eta| < 1.7$. They contain a variety of detector technologies, including: Monitored Drift Tubes (MDTs) and Cathode Strip Chambers (CSCs) used for precision tracking; and Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) used for triggering (see below). All have a granularity between 60 μm to 80 μm in the bending direction.

6.3 Trigger and data acquisition

The periods in which beams circulate the LHC are known as ‘fills’. Typically they last 6 hours [105]. During fills, the ATLAS detector records the output from proton-proton collisions. Each output event requires approximately 1.5 MB of

²Bending power is characterised by the field integral $\int B \, dl$, for a muon with infinite momentum (travelling in a straight line) travelling in a direction orthogonal to the magnetic field B between the innermost and outermost muon chambers.

memory when stored off-line [106]. At the LHC's design luminosity the collision rate in the ATLAS detector is approximately $3.2 \times 10^8 \text{ s}^{-1}$, however, the majority of these collisions do not contain events which are interesting in the context of the ATLAS physics programme.³ Rarer, lower cross-section, and generally more interesting events are selected with a three tier trigger system. This reduces the event rate to a manageable $\sim 200 \text{ Hz}$.

Events are deemed interesting if they contain either high- p_T electrons, photons, jets, hadronically decaying τ -leptons, muons or large missing transverse energy. The primary selection of such events is performed by the Level-1 (L1) trigger. It is hardware based, and reduces the event rate to 75 kHz . A decision to whether or not an event is to be kept is made within $2.5 \mu\text{s}$. This is achieved using information from the EM and hadronic calorimeters as well as sections of the muon spectrometer. On locating a physics object, the L1 trigger creates a region-of-interest (RoI) around it, and passes the object and RoI onto the Level-2 (L2) trigger. The L2 trigger uses partial detector information within the RoI to reconstruct and refine the selection of physics objects. Decisions are made within 40 ms and it reduces the event rate to approximately 3.5 kHz .

The final tier of the trigger system is the Event Filter (EF). It uses the full granularity of the detector systems. Similar algorithms to those used off-line are used to reconstruct physics objects. It takes around 4 s to process each event and reduces the event rate to a final value of $\sim 200 \text{ Hz}$. Events are only written to disk for permanent off-line storage if they pass all three levels of the trigger system.

Data collected by the ATLAS detector is organised into periods and runs. A run generally corresponds to one LHC fill (see above), however, there may be multiple runs per fill, or even runs without circulating beam. A run begins when the beam is stable, and the Data Acquisition (DAQ), detectors and other sub-systems are configured correctly. It might end for several reasons, including problems with the LHC beam. A data period contains a succession of DAQ runs.

³This has increased as of 2015.

Chapter 7

Feasibility study for ZZ production in the $ee/\mu\mu, \tau\tau$ channel

7.1 Introduction

To date, properties of the electroweak W and Z gauge bosons, their production and couplings to fermions have been measured precisely in e^+e^- collisions at LEP, in $p\bar{p}$ collisions at the Tevatron and most recently in pp collisions at the LHC. However, due to the large centre-of-mass energy required to produce di-boson pairs, di-boson production has yet to be measured to a similar precision. The most recent measurements of WW , WZ and ZZ production with e/μ final states are described in [107], [108] and [109]. With a centre of mass energy $\sqrt{s} = 8 \text{ TeV}$, they report production cross-sections of 71.4 pb, 20.3 pb and 7.2 pb respectively, observing very few events. Such measurements currently exclude tau lepton final states since their detection and reconstruction (for reasons described later) is more challenging.

Di-boson production is a significant and irreducible background for the observation of the Higgs boson via several of its decay channels, hence, in order to precisely study the Higgs and determine/constrain properties such as its branching ratios into different observable final states, it is important contributions from di-boson production are well understood. The analysis described in the remainder of this thesis shall focus on the feasibility of observing di-boson ZZ events in which one Z decays to an $ee/\mu\mu$ pair and the other to a $\tau\tau$ pair. The production of ZZ pairs proceeds via the t- and u-channel $q\bar{q}$ interactions, as shown in Figure 7.1. If ZZ production occurs via the s-channel (c.f. Figure 7.1 c) this would lead to an enhancement of ZZ production cross-section relative to that predicted by the Standard Model (c.f. Chapter 1). Any enhancement could also be explained by the presence of undiscovered high mass particles decaying to ZZ .

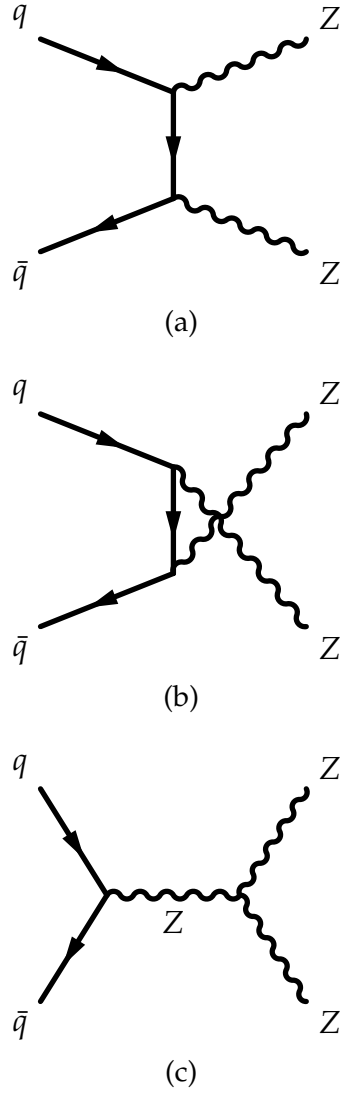


Figure 7.1: Feynman diagrams showing ZZ production via the a) t-channel, b) u-channel and c) s-channel. The latter of these is not included in the SM.

It shall be shown in Section 7.7 that the reconstruction, identification and selection of taus is enhanced at high tau p_T . Furthermore, when a pair of taus is associated to a Z boson, the efficiency of reconstructing the $Z \rightarrow \tau\tau$ improves with high Z boson p_T . Therefore, particularly in the high invariant mass region of interest, the inclusion of tau lepton final states has the potential to add significantly to these low statistics, yet important, di-boson measurements.

7.2 The tau lepton

The tau lepton (τ) is the heaviest lepton with a mass of 1.777 GeV, and will decay either leptonically (τ^{lep}) or hadronically (τ^{had}). It has a short lifetime of 2.9×10^{-13} s and will travel ~ 2 mm before it decays, well within the innermost layer of the ATLAS ID. It can therefore only be identified from its decay products.

In the case of a τ^{lep} decay, these include either an electron or muon accompanied by a neutrino; a signature that is nearly indistinguishable (albeit with an overall softer p_T spectrum) from prompt electrons/muons, making τ^{lep} decays difficult to identify.¹ Whereas for a τ^{had} decay, the visible decay products consist of one or three charged pions usually accompanied by neutral pions. This is a specific signature, allowing for reasonable distinguishing power against other processes. Table 7.1 lists the main decay modes and associated branching ratios of the tau lepton. Hadronic decays are separated into two modes ‘single-prong’ containing a single charged pion, and ‘multi-prong’ containing multiple charged pions.

Leptonic modes	($\sim 35\%$)
$e\nu_e\nu_\tau$	18 %
$\mu\nu_\mu\nu_\tau$	18 %
Hadronic modes: single-prong	($\sim 47\%$)
$\pi^-\nu_\tau$	11 %
$\pi^-\pi^0\nu_\tau$	25 %
$\pi^-\pi^0\pi^0\nu_\tau$	9 %
$\pi^-\pi^0\pi^0\pi^0\nu_\tau$	1 %
$K^- + \text{neutrals}$	1.5 %
Hadronic modes: multi-prong	($\sim 15\%$)
$\pi^-\pi^+\pi^-\nu_\tau$	9 %
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.5 %
$K^-\pi^+\pi^-\nu_\tau$	0.4 %
Other modes	($\sim 3\%$)

Table 7.1: Decay branching fractions of the tau lepton.

Hadronically decaying taus are reconstructed from their decay ‘jet’ of pions. Background QCD processes also produce jets in the ATLAS detector that may be misidentified as a τ^{had} decay. At the LHC, the number of SM physics processes with tau leptons in their final state is overwhelmingly small compared to the large number of QCD processes. Hence proportionally there will be many fake τ^{had} formed from misidentified QCD jets. To discriminate against these, each τ^{had} goes through an identification procedure as described in Section 7.2.2. Leptonically decaying taus are not reconstructed as such in ATLAS.

7.2.1 Reconstruction

Candidate τ^{had} decays are sought by an algorithm that scans through the calorimeters, searching for topological clusters with $E_T > 10$ GeV. Any candidates are marked as a τ^{had} seed. Any surrounding tracks within a cone of $\Delta R < 0.4$, and passing cer-

¹Prompt electrons/muons are those coming from either a W or Z boson decay.

tain quality criteria, are associated to the τ^{had} .² Since only the visible decay products of the τ^{had} are detected in the ATLAS detector, the reconstructed object is referred to as a $\tau^{\text{had-vis}}$.

7.2.2 Identification

After reconstruction, tau identification is achieved with a Boosted Decision Tree (BDT). This finds the optimal separation between signal (correctly identified τ^{had}) and fakes (QCD jets mistakenly identified as τ^{had}) in a multi-dimensional parameter space, summarised below [110]. A ‘BDTJet’ score is then output and attributed to each $\tau^{\text{had-vis}}$. The BDT is trained using QCD background obtained from data, and signal simulated in $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ Monte Carlo (MC) samples (c.f. Section 7.3). Its input parameters include:

Central energy fraction: The fraction of E_T deposited around a $\tau^{\text{had-vis}}$ in the region $\Delta R < 0.1$ (core region), with respect to all E_T in $\Delta R < 0.2$.

Leading track momentum fraction: For the highest- p_T track in the core region, the fraction of the lepton p_T with respect to all E_T in $\Delta R < 0.2$.

Track radius: Using all tracks contained in $\Delta R < 0.4$ of a $\tau^{\text{had-vis}}$, the p_T -weighted distance of tracks to the $\tau^{\text{had-vis}}$ direction.

Leading track IP significance ($S_{\text{leadtrack}}$): The traverse impact parameter for the highest- p_T track in the core region, calculated with respect to the tau vertex, divided by its uncertainty.³

Number of tracks in the isolation region: The number of tracks associated with a $\tau^{\text{had-vis}}$ in the region $0.2 < \Delta R < 0.4$.

Maximum ΔR : Considering only tracks contained in the core region, the maximum ΔR between a track and the $\tau^{\text{had-vis}}$ direction.

Transverse flight path significance (S_T^{flight}): In the transverse plane, the decay length of the secondary vertex, calculated with respect to the tau vertex, divided by its uncertainty. It is defined only for multi-prong $\tau^{\text{had-vis}}$ candidates.

Track mass: Assuming a pion mass for each track, the invariant mass of all tracks in $\Delta R < 0.4$ of a $\tau^{\text{had-vis}}$.

² $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

³The tau vertex is the primary vertex from which the tau originated.

Track-plus- π^0 -system mass: The invariant mass of tracks and π^0 mesons in the core region. ⁴

Number of π^0 mesons: The number of π^0 mesons in the core region.

Ratio of track-plus- π^0 -system p_T : The ratio of tracks-plus- π^0 - p_T to the p_T measured in the calorimeter only.

Leptons, in particular electrons, can also be misidentified as a τ^{had} : electrons will leave a track in the ID and energy deposits in the EM calorimeter; this signature is very similar to a low energy charged hadron, which does not have enough energy to go on and reach the hadronic calorimeter. Besides the parameters used for QCD jet rejection, additional information from other ATLAS sub-detector systems is useful in discriminating against such an occurrence. For example, electrons are more likely to emit transition radiation in the TRT compared to pions. A second BDT algorithm takes several of these discriminating parameters and assigns a ‘BDTElec’ score to each $\tau^{\text{had-vis}}$. This can then be used to veto against $\tau^{\text{had-vis}}$ that are most likely misidentified electrons.

Muons are unlikely to deposit enough energy in the calorimeter to be mistaken for $\tau^{\text{had-vis}}$. Added information from the muon spectrometer also helps in discriminating against such an occurrence. Generally a veto on any $\tau^{\text{had-vis}}$ that overlap loose muon candidates results in sufficient fake rejection.

7.3 Monte Carlo event samples

Monte Carlo event samples are produced using our current best understanding of the SM and its physical processes. Particle interactions and decays are described, after an initial proton-proton collision. There are several steps to the simulation procedure [111]:

Hard process: The simulation starts at the heart of the proton-proton collision with the hard (high momentum-transfer) process. From the partons PDF, the probability (density) distribution for a particular hard scatter is determined using perturbative quantum field theory.

Parton shower: Both the incoming and outgoing partons have colour charge. Therefore, in a process analogous to photon bremsstrahlung from electrically charged particles, partons can radiate gluons. These in turn may produce additional partons, and hence a parton shower. A step-by-step pro-

⁴A π^0 meson has no charge and therefore leaves no track in the ID, only energy deposits in the calorimeters. A description of their reconstruction can be found here [110].

cess, models the parton shower, reducing the momentum transfer scale until the use of perturbation theory is no longer possible.

Hadronisation: The simulated partons are confined into hadrons that can be seen in the detector. In addition to the hard process, proton remnants may form into hadrons. This is known as the ‘underlying event’, and is also simulated at this stage.

Event generation: Many of the simulated hadrons are not stable particles, but in fact heavy resonances that go on to decay. The final stage of the simulation processes models the decay of such resonances.

Various other processes are simulated such as the final state radiation of photons and addition of other simultaneous proton-proton collisions (pile-up). Finally each generated event is passed through a complete simulation of the ATLAS detector, producing simulated hits in the trackers and energy deposits in the calorimeters, from which particles are reconstructed. There are then two levels of information available in the MC samples: generator or ‘truth-level’ – exact knowledge of each simulated particle; and reconstructed or ‘reco-level’ – particles reconstructed from simulated hits and energy deposits in the ATLAS detector.

In generating MC samples, rather than simulating all possible interactions/decays, particular processes are often forced, i.e., the production or decay of a particular particle. These are separated into signal or background samples, depending on the process of interest. In this analysis several MC samples are used to model both the signal and background, including:

Signal:

- ZZ : Example leading order production can be seen in Figure 7.1.
- $Z \rightarrow \tau\tau$: The Drell-Yan production of a $\tau\tau$ pair from a Z boson. This is an important sample for characterising tau selection. However, in the wider analysis it is considered a background.

Background:

- $Z \rightarrow ee$: An example Feynman diagram can be seen in Figure 7.2. There is the potential for initial state partons to hadronise and be misidentified as a tau. Due to the $Z \rightarrow ee$ process having such a large cross-section compared to ZZ (~ 150 times), this is a dominant source of background [112], [113].
- $Z \rightarrow \mu\mu$: The branching ratio for $Z \rightarrow ee$ is equal to $Z \rightarrow \mu\mu$, therefore, its background contribution is equivalent.

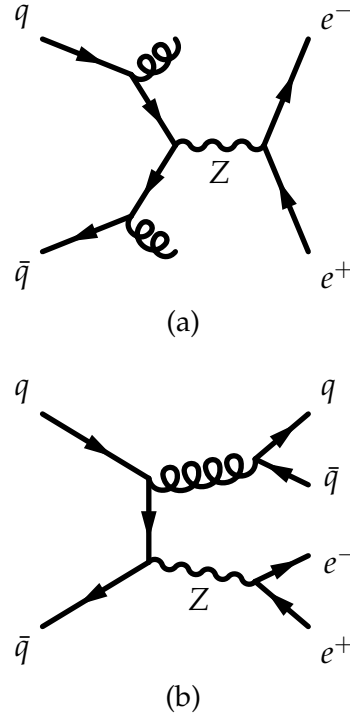


Figure 7.2: Feynman diagrams showing how initial state radiation may be misidentified as a $\tau^{\text{had-vis}}$ pair in $Z \rightarrow ee$ Drell Yan production. In a) a pair of emitted gluons is misidentified, and in b) a $q\bar{q}$ pair.

Lesser, yet still important backgrounds include: WW , WZ and $t\bar{t}$, due to one or more leptons in the final state, and the potential for initial state radiation to be misidentified as a $\tau^{\text{had-vis}}$. In the case of $t\bar{t}$, hadronic decays resulting from W s and b -quarks may also be identified as $\tau^{\text{had-vis}}$. The cross-section for all these processes are smaller than $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$. A summary of the MC samples used in this analysis is given in Table 7.2.

Process	Generator	Channel number	Number of events
ZZ	Herwig++	105986	250 000
$Z \rightarrow \tau\tau$	PowhegPythia	147808	5 000 000
$Z \rightarrow ee$	PowhegPythia	147806	9 500 000
	Sherpa	147770	20 000 000
$Z \rightarrow \mu\mu$	PowhegPythia	147807	9 500 000
	Sherpa	147771	20 000 000
WW	Herwig++	105985	2 000 000
WZ	Herwig++	105987	1 000 000
$t\bar{t}$	PowhegPythia	105861	17 000 000

Table 7.2: A summary of the signal and background MC samples used in this analysis.

7.4 Tau selection

As described in Section 7.2.2, each $\tau^{\text{had-vis}}$ is assigned a BDTJet- and BDTElec-score to help discriminate against fakes caused by QCD jets or electrons. These scores along with the tau p_T , are used for $\tau^{\text{had-vis}}$ selection. Ideally a series of selection cuts would isolate signal from fake taus with 100 % efficiency. Candidate tau leptons at reconstruction level that are matched at truth-level are defined as signal, and fakes those that are not. Reconstructed and truth-level particles are matched if ΔR between their Lorentz vectors is < 0.1 . By definition all taus in the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ MC samples are fakes. Figure 7.3 compares p_T , BDTJet- and BDTElec-score distributions in these samples to signal taus in the $Z \rightarrow \tau\tau$ MC sample.

The p_T distribution for fakes in the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples differ. This is due to the large number of electrons being misidentified as taus. The effect is less so in the $Z \rightarrow \mu\mu$ sample. To remove a reasonable portion of these electron fakes, a selection cut of > 0.5 is applied to the BDTElec-score. The resulting change in the p_T distribution shown in red. There is also a notable change in the BDTJet-score distribution as can be seen in Figure 7.3 g).

By comparing the distributions in Figure 7.3, first order selection cuts on all three parameters are determined. These are improved through a process of scanning each parameter space, having applied the first order cuts on the other parameters, and finding the cut value with optimal signal efficiency and fake rejection. Figure 7.4 shows the efficiency scans. In a) and b) the cut value is equal to the lower bin-edge value. Table 7.3 lists the final cut values.

Variable	Cut
p_T (GeV)	> 20
BDTJet-score	> 0.5
BDTElec-score	> 0.5

Table 7.3: Table showing the final selection cuts applied to $\tau^{\text{had-vis}}$, as determined from the scans in Figure 7.4. Hadronically decaying taus with parameter values above the cut values are kept.

7.4.1 Decay length

A transverse decay length is measured from the primary and secondary vertices associated to each multi-prong $\tau^{\text{had-vis}}$. The significance of this, defined in Section 7.2.2 as S_T^{flight} , is an input parameter to the BDTJet algorithm and affects $\tau^{\text{had-vis}}$ identification. Figure 7.5 compares the S_T^{flight} distribution for signal multi-prong $\tau^{\text{had-vis}}$ in the $Z \rightarrow \tau\tau$ and fakes in the $Z \rightarrow ee/Z \rightarrow \mu\mu$ MC samples. Any

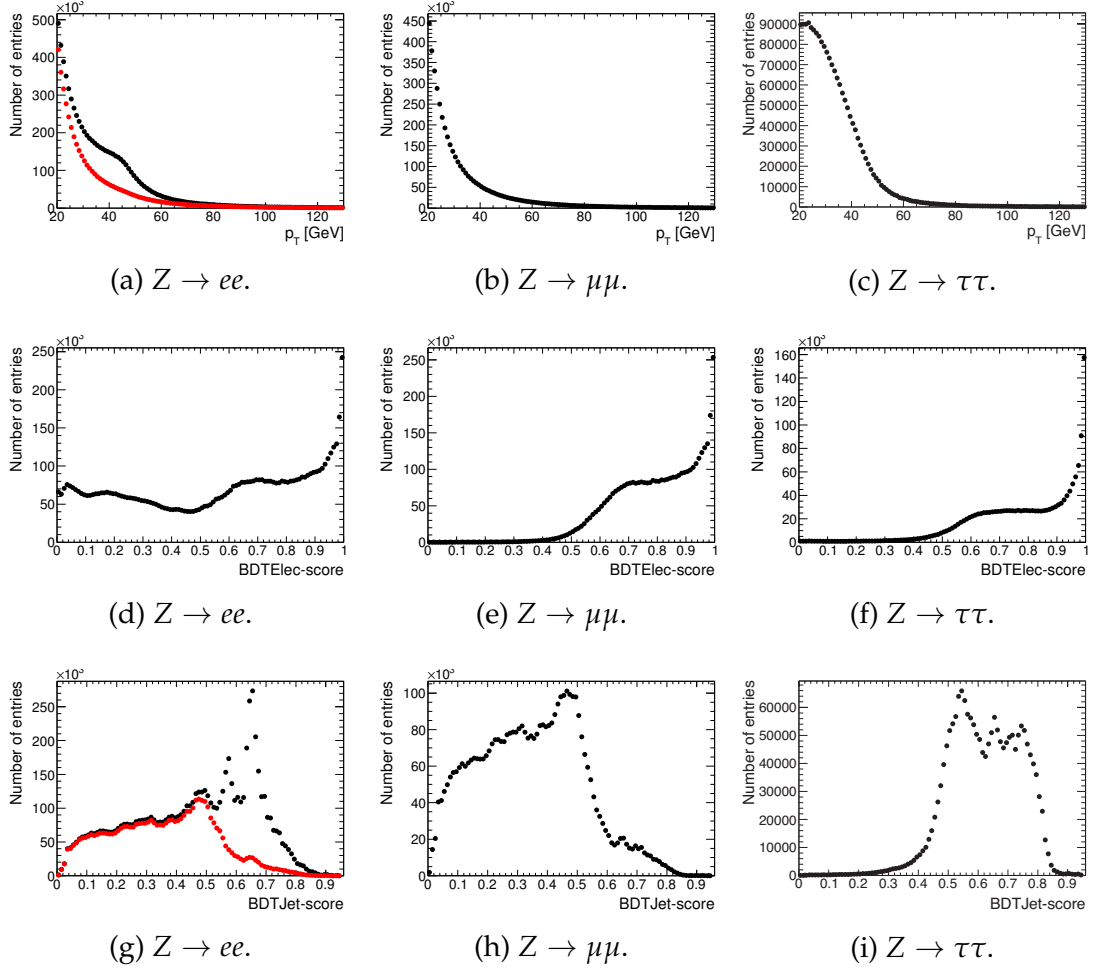


Figure 7.3: Comparison of $\tau^{\text{had-vis}}$ selection distributions for the $Z \rightarrow \tau\tau$, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ MC samples. a) to c) show the tau p_T , d) to f) the BDTElec-score, and g) to i) the BDTJet-score. Entries have not been normalised to sample luminosities, therefore it is only the distribution shapes that are of interest. In the case of $Z \rightarrow ee$, the black and red curves correspond to before and after applying the BDTElec-score cut at 0.5.

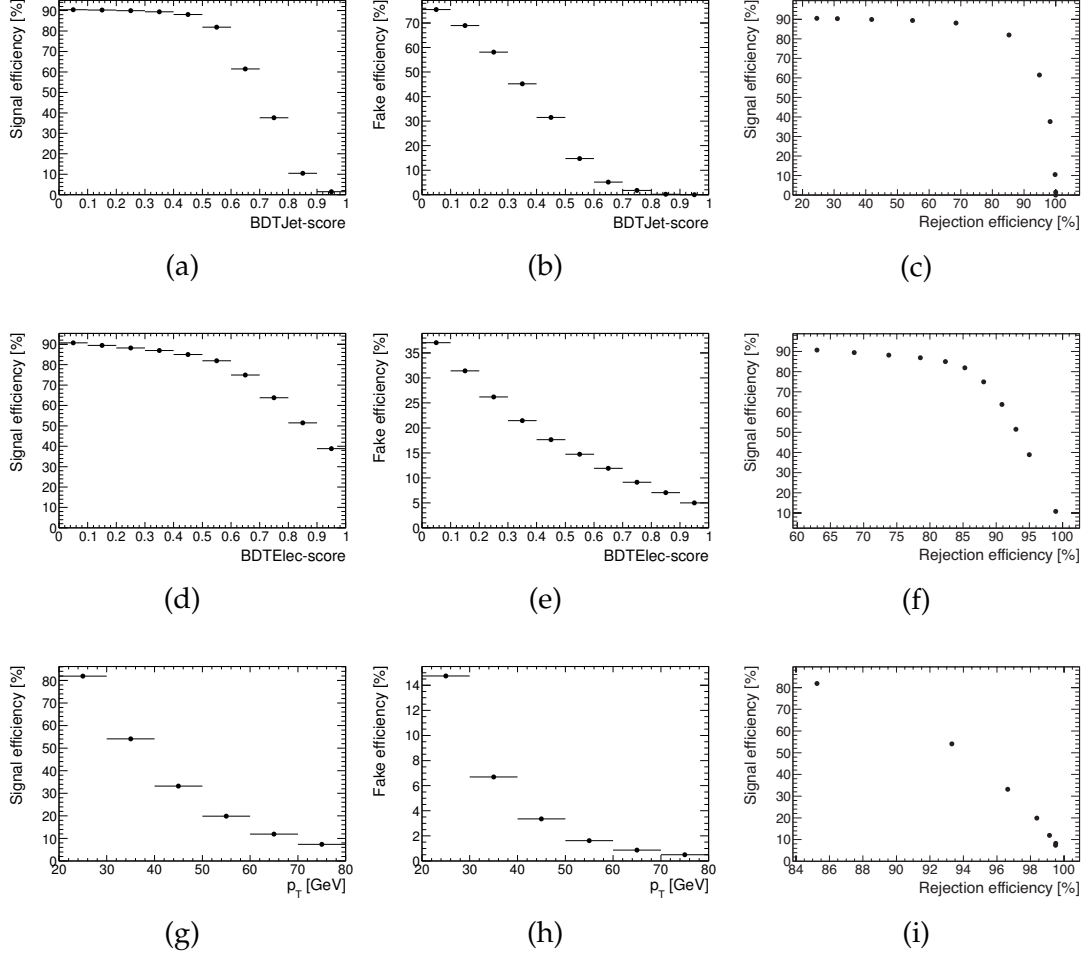


Figure 7.4: Signal efficiency and fake rejection scans for the three parameters listed in Table 7.3, having applied the first order selection cuts. Each row of figures corresponds to a particular parameter. For example, a) shows the efficiency of signal $\tau^{\text{had-vis}}$ passing the BDTJet-score with varying cut value, b) the efficiency of fake $\tau^{\text{had-vis}}$ passing and c) the signal efficiency versus fake rejection efficiency.

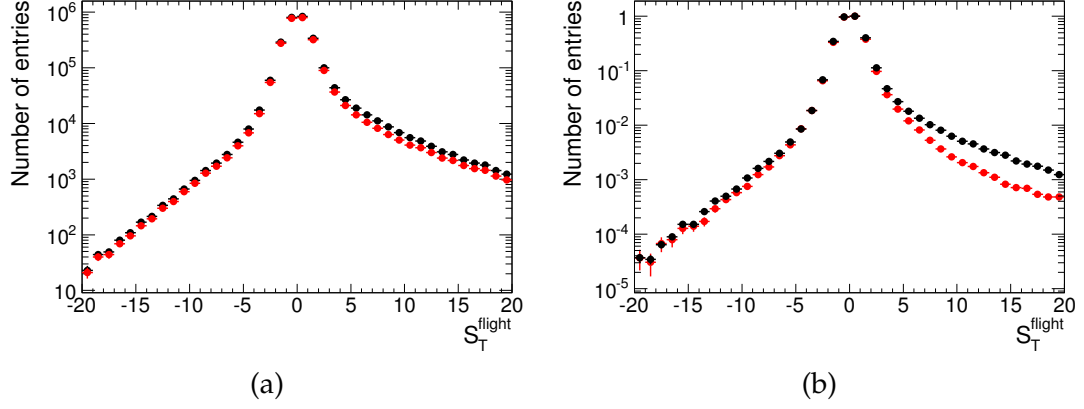


Figure 7.5: The S_T^{flight} measured in each of the MC samples. a) $Z \rightarrow ee$ sample, the black and red curves correspond to before and after applying the BDTElec-score cut respectively. b) direct comparison between the $Z \rightarrow \tau\tau$ sample (red) and $Z \rightarrow \mu\mu$ sample (black), both distributions have been scaled to their peak number of entries.

notable differences between the distributions, as shown in Figure 7.5 b), helps improve the distinguishing power. A value below zero occurs when the measured secondary vertex is placed behind the primary vertex, with regards to the directionality of the decay products. With the addition of the IBL, as discussed in Section 2.2, this input parameter along with the $S_{\text{leadtrack}}$ and others will benefit significantly from the improved ID tracking, enhancing future tau identification.

7.4.2 Invariant mass

In the collision of two particles with mass m_1 and m_2 , the total centre-of-mass energy (E_{cm}) can be expressed in the Lorentz invariant form:

$$\begin{aligned}
 E_{\text{cm}}^2 &= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 \\
 &= m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2) \\
 &= m_1^2 + m_2^2 + 2E_1 E_2 (1 - p_1 p_2 \cos(\alpha))
 \end{aligned} \tag{7.1}$$

where α is the angular separation between the two incoming particles. Since $E_{\text{cm}}^2 = M_{\text{cm}}^2$ (with $c = 1$). We can define an invariant mass $M = M_{\text{cm}}$ with the same parametrisation.

In the case of a particle decay, Equation 7.1 can be used in reverse to determine M of the parent from the energy/momentum, mass and angular separation of its decay products.

7.4.3 Tau pairing

Having passed the selection criteria, taus with a charge product of -1 are paired. If more than one pair is reconstructed in an event, the pair with invariant mass closest to the Z mass (M_Z) is chosen.

7.5 Electron selection

After reconstruction, electrons are split into three identification classifications, labelled: ‘loose++’, ‘medium++’ and ‘tight++’. These are based on a series of parameters measured from the ID and EM calorimeter, including for example, the EM shower shape and impact parameter. They are predefined by the ATLAS Electron-gamma (EG) working group, and designed for general use in all analysis frameworks. From loose++ to tight++ there is a slight reduction in signal efficiency, with gains in fake rejection. To qualify for use in this analysis, electrons must pass the tight++ identification criteria, measured to be $\sim 85\%$ efficient. To further improve signal purity, additional selection criteria are applied, all of which are recommended by the EG working group (as of 2012), and include:

- Author of 1 or 3: The author variable indicates which reconstruction algorithm was used to reconstruct the electron.
- The total transverse energy in a cone of $\Delta R = 0.3$ around the electron candidate, excluding the electron itself, must be less than 3.5 GeV.
- $|\eta| < 2.47$.
- Finally a cut on the electron p_T at 20 GeV is applied.

As for taus, electrons passing the identification and selection criteria are paired if their charge product is equal to -1 . Again, if more than one pair is reconstructed for a given event, the pair with invariant mass closest to the Z mass is chosen.

7.6 Muon selection

With the added information from the MS, in general the reconstruction of muons is cleaner than that of taus and electrons. To be used in this analysis muons must be identified as ‘combined’. This means tracks in the ID and MS are consistent with one another and can be combined together. Energy losses due to interactions in the calorimeter are taken into account when extrapolating tracks from the MS

into the ID and vice-versa. Additional selection criteria recommended by the ATLAS Muon Combined Performance (MCP) group include:

- Muons must produce at least 1 hit in the pixel detector b-layer, at least 2 hits across all pixel detector layers, and at least 6 hits in the SCT.
- Across all silicon layers, there must be fewer than 3 holes (missing hit when expected).
- Muons with $|\eta| < 1.9$ must have TRT hits + TRT outliers > 5 , and the outlier fraction, $N_{\text{outliers}} / (N_{\text{hits}} + N_{\text{outliers}}) < 0.9$. An outlier is defined as a hit that is not included in the final track parameter determination because its χ^2 contribution is too high.
- The total transverse energy in a cone of $\Delta R = 0.3$ around the muon candidate, excluding the muon itself, must be less than 4 GeV.
- Finally a cut on the muon p_T at 20 GeV is applied.

If one or more muons are present in an event, they are paired in the same way as taus and electrons.

7.7 Detection efficiency

For truth-level electrons, muons and taus (τ^{had}), the efficiency of their reconstruction, identification and selection, or simply their overall detection, versus p_T is shown in Figure 7.6. This is having satisfied the above criteria in the $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$ MC samples. The corresponding truth-level p_T distributions are shown to give an idea of event frequency. For taus, there is a large increase in the measured detection efficiency from 0 GeV to 100 GeV. A similar trend is also apparent in the detection of tau pairs, i.e., the combined efficiency of detecting both taus in the event. In the decay of a Z boson, taus are preferentially emitted back-to-back. When the initial Z boson has a large amount of p_T , the emitted tau pair is Lorentz boosted, and in the lab-frame there is a small $\Delta\phi$ measured between the two [114]. Figure 7.7 shows the correlation between the tau pair p_T , $\Delta\phi$, and detection efficiency. One can see in the high p_T region of the Z boson, and small $\Delta\phi$ of the emitted taus, this is enhanced. For comparison, equivalent plots for electron and muon pairs are shown, where a similar trend is observed. This enhancement coincides with the region most interesting for potentially observing new physics, and from now on it shall be referred to as the ‘region of interest’. However, the reader should also bare in mind the small number of events that fall within this region, compared to the total.

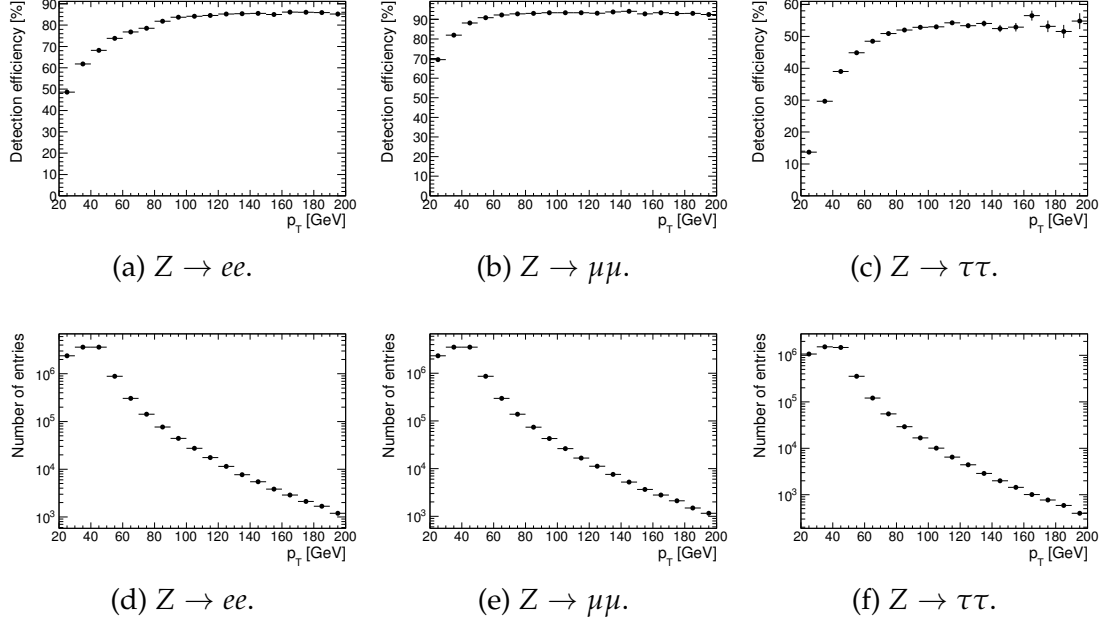


Figure 7.6: The upper plots a), b) and c) show the combined reconstruction, identification and selection (detection) efficiencies versus truth-level p_T for electrons from the $Z \rightarrow ee$ MC sample, muons from the $Z \rightarrow \mu\mu$ MC sample and $\tau^{\text{had-vis}}$ from the $Z \rightarrow \tau\tau$ MC sample. To give an idea of event frequency, the lower plots d), e) and f) show the corresponding truth-level p_T distributions.

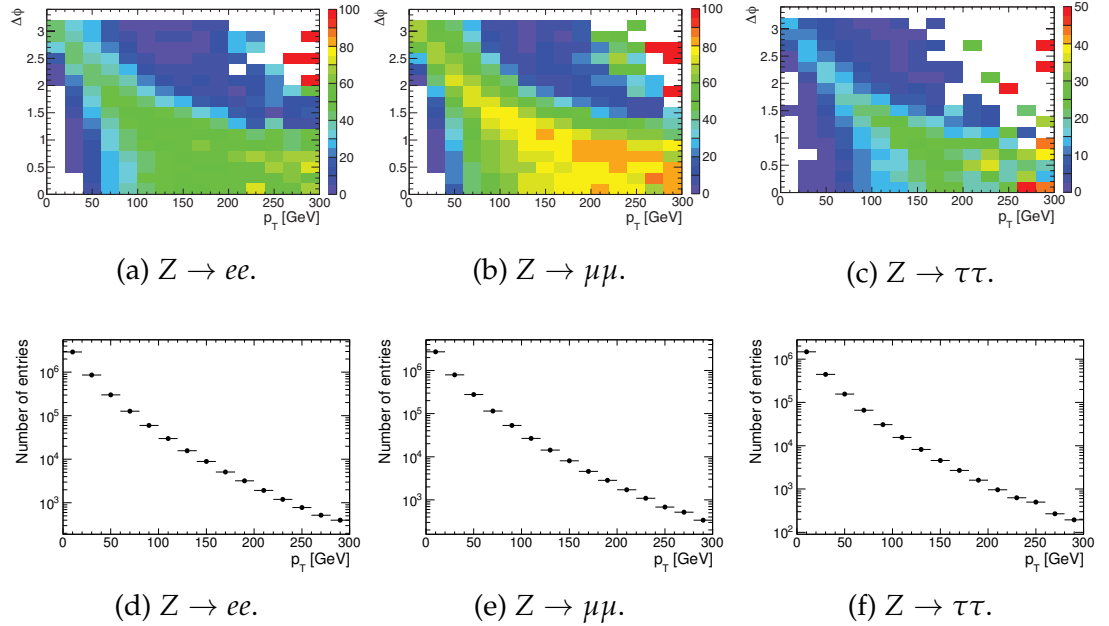


Figure 7.7: The upper plots a), b) and c) show the detection efficiencies versus truth-level p_T and $\Delta\phi$ for electron pairs from the $Z \rightarrow ee$ MC sample, muon pairs from the $Z \rightarrow \mu\mu$ MC sample and $\tau^{\text{had-vis}}$ pairs from the $Z \rightarrow \tau\tau$ MC sample. In c) there is a scale change in comparison to a) and b), when calculating the efficiency, only τ^{had} pairs are taken into account. The lower plots d), e) and f) show the corresponding truth-level pair p_T distributions, where again in f) only τ^{had} pairs are included. Note, this is the combined efficiency to detect both objects in the event.

7.8 Overlap removal

It is possible for the same physical object to be duplicated and reconstructed as two separate objects in the detector. In this analysis, there are three types of object overlap removal: μ/e , e/τ and μ/τ . For the purposes of overlap removal, the identification criteria for electrons is reduced to loose++ and p_T cut to 10 GeV. Likewise, the p_T cut for muons is reduced to 10 GeV. Since muons have the cleanest reconstruction and identification, any taus matched to muons with $\Delta R < 0.1$, are likely fakes and removed. Muons can radiated photons that may convert to an electron-positron pair, therefore any electrons matched to muons with $\Delta R < 0.1$ are removed. If any remaining electrons are matched to taus with $\Delta R < 0.1$, the tau is removed.

7.9 Event selection

For both data and MC, having reconstructed all physics objects, applied identification/selection cuts, and gone through a process of overlap removal, an event selection is applied. The first requirement is for the presence of exactly one ee or $\mu\mu$ pair with $|M_{ll} - M_Z| < 10 \text{ GeV}$.⁵ This ensures a $Z \rightarrow ee/\mu\mu$ decay. If both an ee and $\mu\mu$ pair are present, the event is discarded. Finally, the event is selected for further analysis if an additional single $\tau^{\text{had-vis}}$ pair is present.

A second class of cuts are applied only to data. These ensure the removal of events in which the sub-detectors were not functioning properly (exclusion from the Good Runs List), or in which the data was corrupted. A summary of the event selection is given in Table 7.4.

Data and MC
single $ee/\mu\mu$ pair with $ M_{ll} - M_Z < 10 \text{ GeV}$
single $\tau^{\text{had-vis}}$ pair
Data
Inclusion in the Good Runs List
Reject events with LAr noise bursts (EM calorimeter)
Reject events with corrupt hadronic calorimeter data

Table 7.4: Summary of event selection so far.

⁵The value of M_Z is taken to be 91 GeV [115].

Chapter 8

Missing transverse energy

8.1 Introduction

In Table 7.1 the decay modes of the tau are listed. In each case the final products include a ν_τ . Neutrinos, being very weakly interacting, leave no tracks or energy deposits in the ATLAS detector, and their presence is inferred only from the missing energy/momentum in a collision. As described in Section 1.3, we can only be sure of each collision's approximately non-zero momentum in the transverse plane, and therefore only a missing transverse energy (E_T^{miss}) can be determined. In signal events ($Z \rightarrow ee/\mu\mu$ and $Z \rightarrow \tau\tau$) both tau decays will include a ν_τ in the final state, and therefore some amount of E_T^{miss} is expected. The following sections describe an analysis of the E_T^{miss} .

8.2 E_T^{miss} reconstruction

The E_T^{miss} is measured using an algorithm defined by the ATLAS missing E_T group. It takes the energy deposits of electrons, muons, taus and jets as inputs. For muons, the energy/momentum measurement is obtained from the combined muon, i.e., including measurements from the MS. For all other objects, it is obtained from the EM and hadronic calorimeters, and the topological cluster associated to each object. If any energy corrections are applied to reconstructed objects (c.f. Section 9.2) these are propagated to the calculation of the E_T^{miss} . For example, if the energy of an electron is increased, the E_T^{miss} is updated to ensure overall conservation of energy/momentum. In general, the E_T^{miss} is measured as a two-vector, $\vec{E}_T^{\text{miss}}$, with magnitude, E_T^{miss} , and direction, ϕ .

8.3 E_T^{miss} analysis

Consider a Z boson produced with high p_T decaying to two taus. The taus themselves go on to decay either hadronically or leptonically. Since the tau lepton has a comparatively large amount of p_T , in comparison to the mass of its decay products, all, including the ν_τ , are assumed to travel in a direction collinear to the parent tau. The measured E_T^{miss} will be approximately equal to the vector sum of the two ν_τ momenta: $\vec{E}_T^{\text{miss}} \sim \vec{p}_T(\nu_{\tau_1}) + \vec{p}_T(\nu_{\tau_2})$. If the two taus are emitted back-to-back, the vector addition of $\vec{p}_T(\nu_{\tau_1})$ and $\vec{p}_T(\nu_{\tau_2})$ will approximately cancel and result in a small value of E_T^{miss} . Furthermore, if either one of the tau-neutrinos has significant p_T , a slight deviation from its parent tau direction will have a significant effect on the vector sum. In the case where the two taus are emitted with small angle between the two, the vector addition of $\vec{p}_T(\nu_{\tau_1})$ and $\vec{p}_T(\nu_{\tau_2})$ is likely to result in a significant value of E_T^{miss} . This will be more robust to deviations in ν_τ direction, and for this reason is considered "well defined".

For the $Z \rightarrow \tau\tau$ and $Z \rightarrow ee/\mu\mu$ MC samples, Figure 8.1 shows the invariant mass of the $\tau^{\text{had-vis}}$ pair versus E_T^{miss} for pairs with $\Delta\phi < 1$ (i.e. well defined). In the $Z \rightarrow \tau\tau$ sample, there is a negative correlation between the two observables that is not present in the $Z \rightarrow ee/\mu\mu$ samples and can be explained by the following: the total invariant mass of the system must be conserved and equal to the Z boson mass, within a certain width. Therefore, if more energy/momentum is retained by the visible decay products, less remains for the ν_τ and vice-versa, affecting the measured E_T^{miss} . The same is not true in the case of the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples, where by definition the $\tau^{\text{had-vis}}$ are fakes, and there is less likely a constraint on the E_T^{miss} with regards to the Z boson mass.

Several additional selection cuts can be applied to the E_T^{miss} to take advantage of this correlation and help discriminate against fake events: a cut on its magnitude, or requirement for it to lie within the small-angle sector of the $\tau\tau$ pair.¹ However, an improved method might be achieved in taking advantage of the constraint on the invariant mass of the system; in essence, determining whether the direction and magnitude of the E_T^{miss} is consistent with the direction and visible p_T of the two taus.

8.4 Tau-neutrino momentum calculated from the E_T^{miss}

This section describes a method for determining the momentum of each ν_τ from the E_T^{miss} . Figure 8.2 shows a schematic representation of a $\tau\tau$ pair produced in

¹The angle $\Delta\phi$ between the two taus can be measured either clockwise or anti-clockwise. The region defined by the smaller of these two angles is referred to as the 'small-angle' sector.

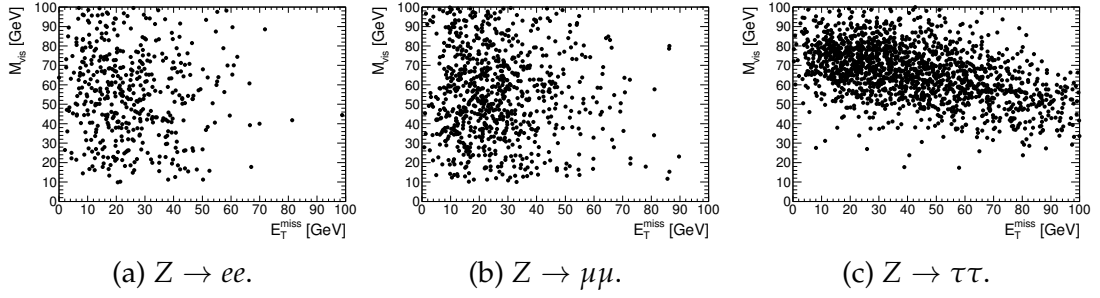


Figure 8.1: The correlation between the E_T^{miss} and the visible invariant mass (M_{vis}) of the $\tau^{\text{had-vis}}$ pair, for the a) $Z \rightarrow ee$, b) $Z \rightarrow \mu\mu$ and c) $Z \rightarrow \tau\tau$ MC samples. All pairs have $\Delta\phi < 1$.

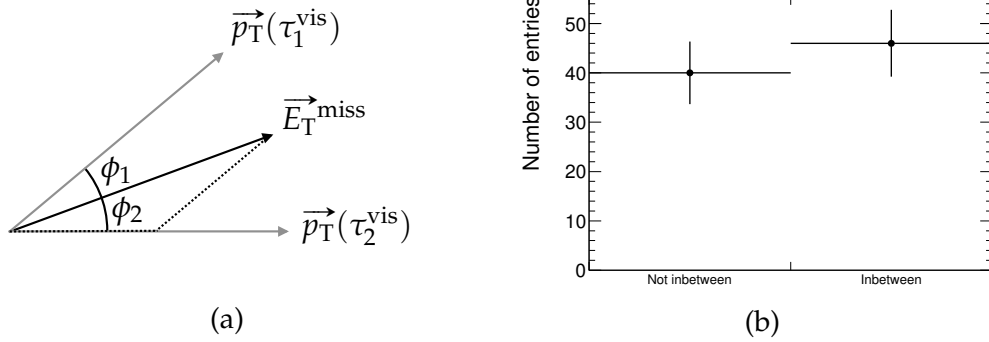


Figure 8.2: When the E_T^{miss} lies within the small-angle sector of the $\tau\tau$ pair, it can be decomposed to infer the ν_τ momentum vectors. Figure a) shows a schematic representation of this scenario, whereas b) shows the relative number of events in which the E_T^{miss} lies in and outside the small-angle sector as determined from the ZZ MC sample, after having applied the $Z \rightarrow ee/\mu\mu$ selection.

a Z decay. The visible decay products are reconstructed, and there is a measured $\vec{E}_T^{\text{miss}}$ that can be decomposed to infer $\vec{p}_T(\nu_{\tau_1})$ and $\vec{p}_T(\nu_{\tau_2})$. A three-momenta for each ν_τ can then be determined using the relations:

$$p_x = p_T \cos(\phi), \quad (8.1)$$

$$p_y = p_T \sin(\phi), \quad (8.2)$$

$$p_z = p_T \sinh(\eta), \quad (8.3)$$

There is some uncertainty attributed to the measurement of the $\vec{E}_T^{\text{miss}}$ (c.f. Section 8.5.1). As such, there are likely legitimate signal events in which the $\vec{E}_T^{\text{miss}}$ lies outside the small-angle sector of the $\tau\tau$ pair, as can be seen in Figure 8.2 b). When this is the case, using the above method results in a physically unfeasible scenario where one or both tau-neutrinos requires negative momenta. This being so, the method is only applicable to a sub-set of events – i.e., when the $\vec{E}_T^{\text{miss}}$ lies within the small-angle sector of the $\tau\tau$ pair.

8.5 Tau-neutrino momentum calculated from the $\tau\tau$ pair

This section describes a method for determining a momentum range for each ν_τ , which is consistent with the $\tau\tau$ pair visible p_T and the constraint on the Z boson mass. In general, taus emitted from a Z decay have a high p_T (> 20 GeV) in comparison to their rest mass, and they can be assumed massless. As such, the invariant mass, given by Equation 7.1, simplifies to:

$$M^2 = 2p_{\tau_1}p_{\tau_2}(1 - \cos(\alpha)) \quad (8.4)$$

where p_{τ_1} and p_{τ_2} are the momentum three-vectors of τ_1 and τ_2 . If M is constrained to the Z mass, M_Z , the dependency of p_{τ_1} on p_{τ_2} is equal to:

$$p_{\tau_1} = \frac{M_Z^2}{2p_{\tau_2}(1 - \cos(\alpha))} \quad (8.5)$$

Again, assuming all decay products are collinear to their parent tau then $p_{\tau_1} = p(\tau_1^{\text{vis}}) + p(\nu_{\tau_1})$ and $p_{\tau_2} = p(\tau_2^{\text{vis}}) + p(\nu_{\tau_2})$, where τ^{vis} are the visible decay products, and Equation 8.5 becomes:

$$p(\nu_{\tau_1}) = \frac{M_Z^2}{2(p(\tau_2^{\text{vis}}) + p(\nu_{\tau_2}))(1 - \cos(\alpha))} - p(\tau_1^{\text{vis}}) \quad (8.6)$$

Using the visible three-momenta, a range of possible ν_τ three-momentum values are calculated. Figure 8.3 shows this for a particular signal event in the ZZ MC sample. In this event the $\vec{E}_T^{\text{miss}}$ lies within the small-angle sector of the $\tau\tau$ pair. It has been decomposed, using the method described in Section 8.4, and marked on the figure. Using truth-level information an equivalent range has been calculated using the truth-tau visible three-momentum. The truth- E_T^{miss} and truth- ν_τ three-momentum are known and marked on the figure. An equivalent plot for an event in which the $\vec{E}_T^{\text{miss}}$ did not lie within the small-angle sector is shown for comparison, in this case it was not possible to decompose the measured $\vec{E}_T^{\text{miss}}$.

8.5.1 E_T^{miss} uncertainty

The uncertainty on the $\vec{E}_T^{\text{miss}}$ in both magnitude, $\sigma_{E_T^{\text{miss}}}$, and ϕ , σ_ϕ , is estimated by comparison to the truth- E_T^{miss} in the $Z \rightarrow \tau\tau$ MC sample. The truth- E_T^{miss} is an event variable made available by the ATLAS missing E_T group and calculated from truth-level vector sum of all non-interacting particles. Residuals are calcu-

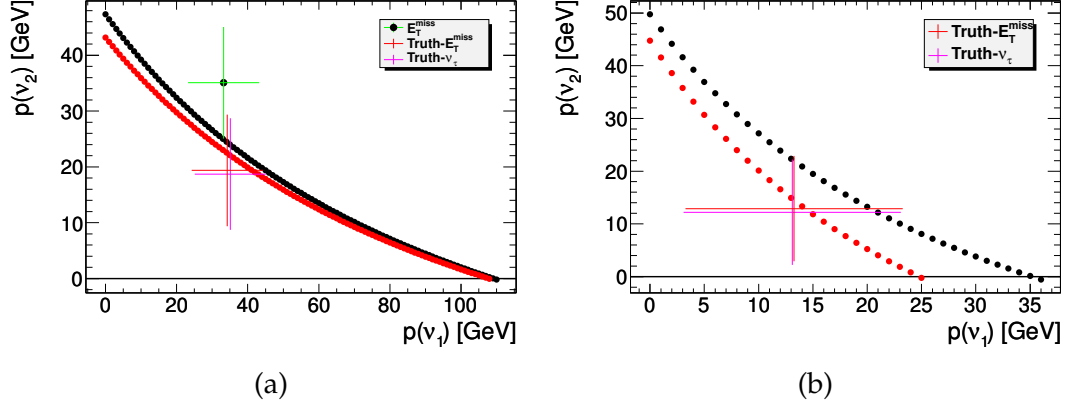


Figure 8.3: The ν_τ three-momentum range calculated using Equation 8.6, for a) an event in which the E_T^{miss} lies within the small-angle sector of the $\tau\tau$ pair and b) an event in which it does not. The black curve is calculated from the reco-tau visible three-momentum and the red curve from the truth-tau visible three-momentum. The green marker corresponds to the ν_τ momentum decomposed from the E_T^{miss} and the red marker to the ν_τ momentum decomposed from the truth- E_T^{miss} . The truth- E_T^{miss} is an event variable made available by the ATLAS missing E_T group and calculated from truth-level vector sum of all non-interacting particles. The purple marker corresponds to the truth- ν_τ momentum. Note in b) the green marker is missing since the E_T^{miss} does not lie within the small-angle sector of the $\tau\tau$ pair and therefore it is not possible to decompose.

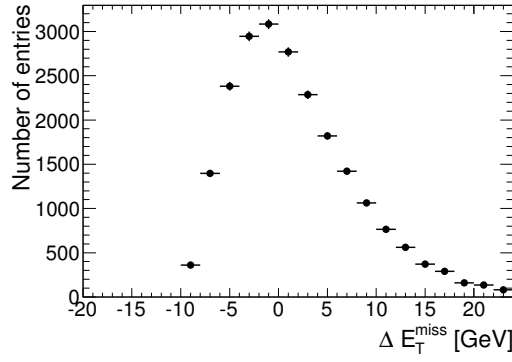
lated with: $\Delta E_T^{\text{miss}} = (\text{truth-}E_T^{\text{miss}} - E_T^{\text{miss}})$ and $\Delta\phi = (\text{truth-}\phi - \phi)$. Figures 8.4 a) and b) show the measured ΔE_T^{miss} and $\Delta\phi$ for events with E_T^{miss} between 10 GeV and 20 GeV. The root mean square (RMS) of each distribution is used to estimate $\sigma_{E_T^{\text{miss}}}$ and σ_ϕ respectively. There is a positive skew observed in Figure 8.4 a), which is not fully understood. However, to reduce its effect, the range is first restricted to $\pm 2 \times \text{RMS}$, before the RMS of the reduced range used to estimate $\sigma_{E_T^{\text{miss}}}$. This technique of range restriction is also used when estimating σ_ϕ to reduce the effect of large distribution tails. For E_T^{miss} values from 0 GeV to 100 GeV Figure 8.4 c) and d) show the variation of $\sigma_{E_T^{\text{miss}}}$ and σ_ϕ over the range respectively.

8.5.2 E_T^{miss} consistency

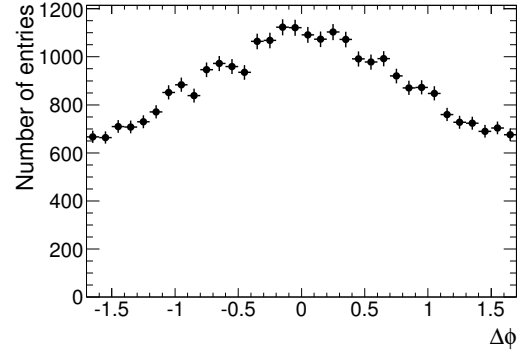
For each point in the ν_τ three-momentum range, a transverse two-momenta, $\vec{p}_T(\nu_\tau)$, is determined, and the vector sum of $\vec{p}_T(\nu_{\tau_1}) + \vec{p}_T(\nu_{\tau_2})$ compared directly to the $\vec{E}_T^{\text{miss}}$. A consistency parameter is defined by:

$$\Delta\mathcal{E}_T^{\text{miss}} = \left(\left(\frac{\delta E_T^{\text{miss}}}{\sigma_{E_T^{\text{miss}}}} \right)^2 + \left(\frac{\delta\phi}{\sigma_\phi} \right)^2 \right)^{\frac{1}{2}} \quad (8.7)$$

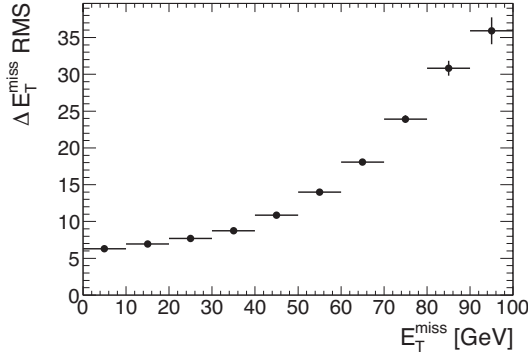
Here the value of δE_T^{miss} and $\delta\phi$ are the difference, in magnitude and ϕ , between



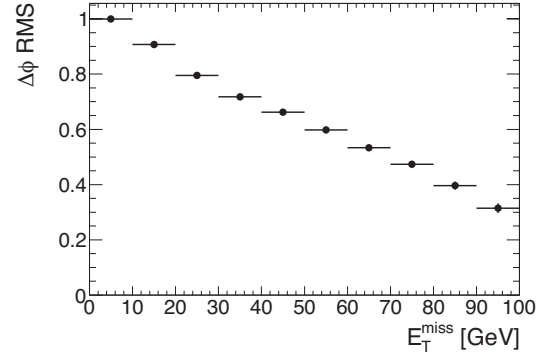
(a)



(b)



(c)



(d)

Figure 8.4: a) and b) show residuals measured by comparing E_T^{miss} to the truth- E_T^{miss} in the $Z \rightarrow \tau\tau$ MC sample for events with E_T^{miss} between 10 GeV and 20 GeV. Figures c) and d) show how the RMS of ΔE_T^{miss} and $\Delta\phi$ vary across the range.

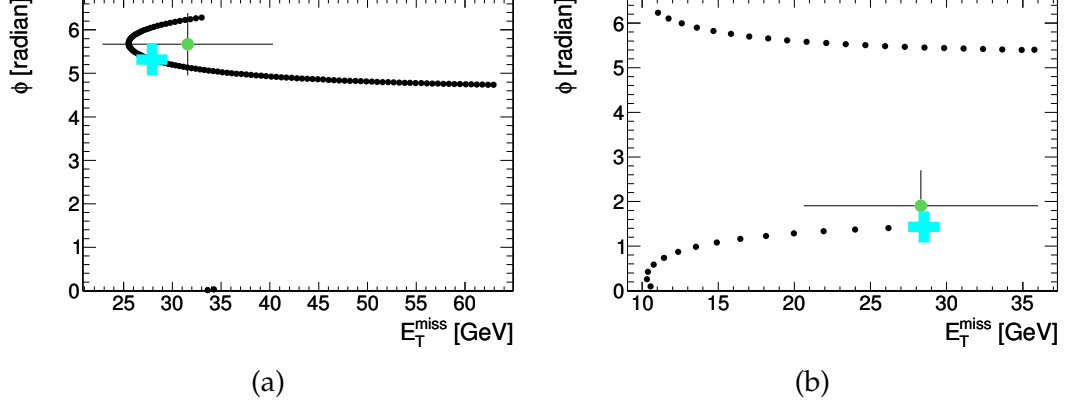


Figure 8.5: For the same events, a) and b), as shown in Figure 8.3, the vector sum of $p_T(\nu_{\tau_1}) + p_T(\nu_{\tau_2})$ (black curve) compared to the E_T^{miss} (green marker). The point on the curve corresponding to the minimum $\Delta\mathcal{E}_T^{\text{miss}}$ is marked with a blue cross. This time a comparison can be made to the E_T^{miss} in both cases.

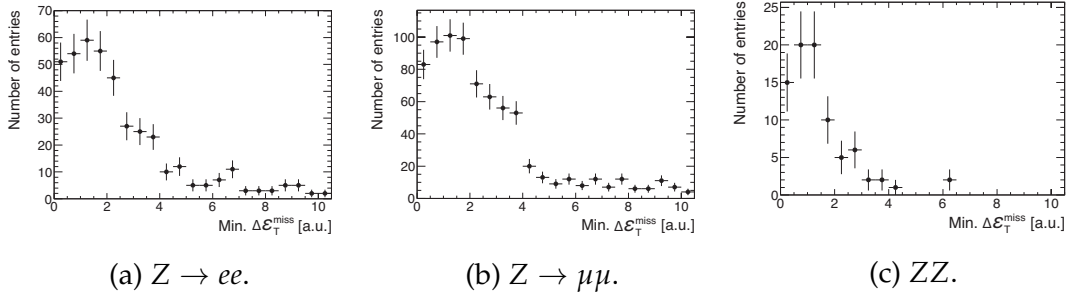


Figure 8.6: The value of minimum $\Delta\mathcal{E}_T^{\text{miss}}$ determined from a) fake $\tau^{\text{had-vis}}$ pairs in the $Z \rightarrow ee$, b) fake $\tau^{\text{had-vis}}$ pairs in the $Z \rightarrow \mu\mu$ and c) signal $\tau^{\text{had-vis}}$ pairs in the ZZ MC samples. Entries have not been normalised to sample luminosities.

the vector sum and the $\vec{E}_T^{\text{miss}}$. They are divided by their respective uncertainties, as measured in the previous section. For the same events shown in Figure 8.3, Figure 8.5 compares the vector sum range to the event $\vec{E}_T^{\text{miss}}$. The point with minimum $\Delta\mathcal{E}_T^{\text{miss}}$ is marked with a blue cross. Only now is a comparison possible when the $\vec{E}_T^{\text{miss}}$ does not lie within the small-angle sector of $\tau^{\text{had-vis}}$ pair. Clearly it is consistent in both cases.

The newly defined parameter is only of use if it provides additional discrimination power against fake $\tau^{\text{had-vis}}$ pairs. To evaluate this, Figure 8.6 compares the minimum $\Delta\mathcal{E}_T^{\text{miss}}$ measured for signal in the ZZ , and fakes in the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ MC samples. This is having applied the selection criteria, as defined in Table 7.4. In general, the visible p_T and direction of $\tau^{\text{had-vis}}$ pairs in signal events is more consistent with the measured $\vec{E}_T^{\text{miss}}$ than in background, as one would expect.

8.6 Method comparison

The performance of the $\Delta\mathcal{E}_T^{\text{miss}}$ parameter is compared to one dimensional cuts on the $\vec{E}_T^{\text{miss}}$ magnitude and direction. For the latter this refers to whether or not the $\vec{E}_T^{\text{miss}}$ lies within the small-angle sector of the $\tau^{\text{had-vis}}$ pair. In each case, Figure 8.7 shows the signal efficiency versus fake rejection for varying cut value, again having applied the event selection detailed in Table 7.4. In the case of $\Delta\mathcal{E}_T^{\text{miss}}$ selection, a reverse cut is applied, i.e., removing events with minimum $\Delta\mathcal{E}_T^{\text{miss}}$ above the cut value. A ‘line of futility’ has been drawn to highlight potential gains. Although not dramatically so, the $\Delta\mathcal{E}_T^{\text{miss}}$ appears to have an improved performance over the other two, with a measured signal efficiency of 81 % and fake rejection of 42 %. The next best, is a cut on the E_T^{miss} , with a signal efficiency of 80 % and fake rejection of 40 %. Having established this to be the case, albeit with an unfortunately very marginal performance gain, its inclusion towards the final event selection shall be detailed in the next chapter.

8.7 Summary

A new discrimination parameter has been defined. It uses the visible p_T of each tau from a $Z \rightarrow \tau\tau$ decay and evaluates a range of possible ν_τ three-momenta; taking into account the fact that the total invariant mass must be conserved and equal to the Z boson mass. The corresponding vector sum of ν_τ two-momenta, $\vec{p}_T(\nu_{\tau_1}) + \vec{p}_T(\nu_{\tau_2})$, is then compared directly to the measured E_T^{miss} . In general, signal events were found to be more consistent than fake events, with a smaller minimum $\Delta\mathcal{E}_T^{\text{miss}}$ measured. Discriminating in this way does not require the $\vec{E}_T^{\text{miss}}$ to lie within the small-angle sector of the $\tau\tau$ pair. Its performance was compared to other potential one-dimensional cuts on the $\vec{E}_T^{\text{miss}}$, where it proved better at retaining signal whilst removing fake events.

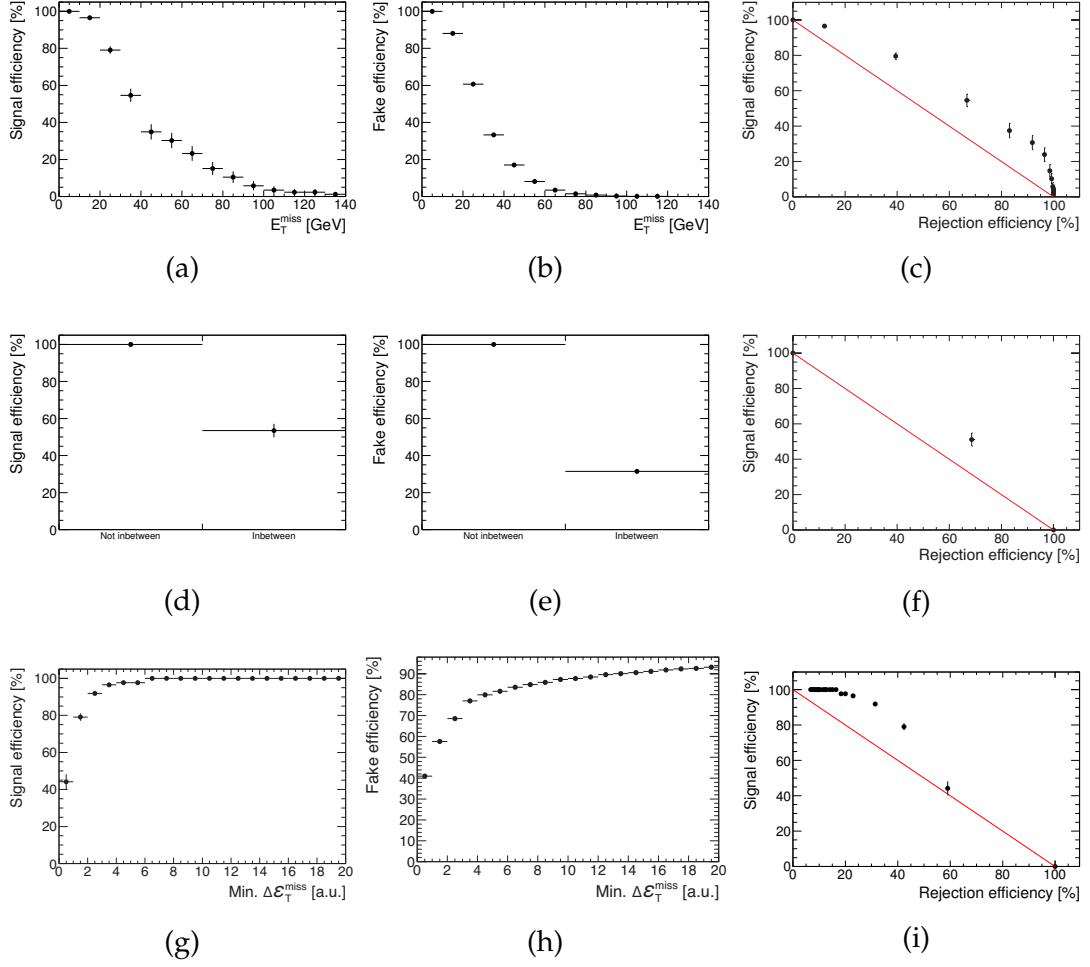


Figure 8.7: Signal efficiency and fake rejection scans comparing cuts on the E_T^{miss} magnitude and direction to the newly defined parameter, ΔE_T^{miss} . Each row corresponds to a particular parameter: a) to c) E_T^{miss} magnitude, d) to f) E_T^{miss} direction and g) to i) minimum $\Delta\mathcal{E}_T^{\text{miss}}$.

Chapter 9

Data and model comparison

9.1 Introduction

Data samples are formed from three ATLAS Off-line Data (AOD) streams: 'Jet-tau- E_T^{miss} ', 'Electron-gamma' and 'Muon'. Events are placed into these depending on which triggers were fired (single electron, di-muon etc.) during data taking. Since more than one trigger may be fired per event, it is possible for a single event to be placed in more than one stream and duplicated in data.

In this analysis the reconstruction of an ee or $\mu\mu$ pair is required before a $\tau\tau$ pair is sought, hence only the Electron-gamma and Muon streams are analysed. Duplicate events are removed by exclusively reconstructing ee pairs when analysing the Electron-gamma stream and $\mu\mu$ pairs when analysing the Muon stream, $\tau\tau$ pairs are reconstructed in both cases.

The data/model agreement is examined with several control distributions. These are an important cross-check to ensure the selected MC samples model both the signal and background well. At the time of MC production, the exact data taking conditions are not known. Therefore, before any comparison can be made, several corrections must be applied to the MC, or occasionally to the data.

9.2 Corrections for known disagreements

Corrections can roughly be divided into two groups: those that affect object selection, i.e., corrections to an object's energy etc.; and those that affect the probability of observing a particular event, for which an overall event weight is prescribed.

9.2.1 Electron energy scale and resolution

For electrons, any discrepancy in the response of the calorimeter between data and MC can be corrected by a ‘scale’ and ‘resolution’ correction. The scale correction is parametrised by [103]:

$$E_{\text{data}} = (1 + \alpha(\eta)) E_{\text{MC}} \quad (9.1)$$

where E_{data} and E_{MC} are the electron energies in data and MC respectively. The parameter $\alpha(\eta)$ accounts for a deviation from the optimum calibration and is dependent on η . Its value is determined by finding the best agreement in the position of the well defined $Z \rightarrow ee$ resonance.

The resolution is corrected by applying a Gaussian smearing to the MC [103]. The amount of smearing to apply, is again determined by finding the best agreement with the $Z \rightarrow ee$ resonance.

9.2.2 Muon momentum resolution

The muon momentum is accurately measured from the combined muon. No scaling is required, however, as for electrons, the resolution is corrected by applying a Gaussian smearing, this time determined from the $Z \rightarrow \mu\mu$ resonance.

9.2.3 Reconstruction, identification, trigger and isolation efficiencies

For each stage of electron/muon reconstruction, identification and selection, there is an associated efficiency. This being so, an overall detection efficiency is written as:

$$\epsilon_{\text{detection}} = \epsilon_{\text{reconstruction}} \times \epsilon_{\text{identification}} \times \epsilon_{\text{trigger}} \times \epsilon_{\text{isolation}} \quad (9.2)$$

where $\epsilon_{\text{trigger}}$ is the efficiency for an electron/muon to trigger the ATLAS detector and $\epsilon_{\text{isolation}}$ the efficiency for an electron/muon to pass the isolation requirements. All the values shown in Equation 9.2 are obtained for data and MC, using the ‘tag-and-probe’ method described below. Scale Factors (SF), defined in Equation 9.3, are then determined as a function of η and E_T .

$$\text{SF}_{\text{MC}} = \frac{\epsilon_{\text{data}}}{\epsilon_{\text{MC}}} \quad (9.3)$$

The tag-and-probe method measures lepton efficiencies using clean, unbiased and well-understood samples, such as the $Z \rightarrow ll$ resonance [116]. First a ‘tag’

lepton is sought, required to pass strict identification and selection criteria; followed by a ‘probe’ lepton, that is required to pass much looser criteria. The invariant mass of the combined tag-probe pair must fall within a window surrounding the Z resonance. Then, for each lepton criterion, such as lepton reconstruction, isolation etc., an efficiency is defined as the number of probe leptons passing the criterion divided by the total number of probe leptons.

9.2.4 Tau corrections

An energy scale correction is applied to taus. As before, the correction factor is determined through finding the best agreement between data and MC of the $Z \rightarrow \tau\tau$ resonance [110].

The tau detection efficiency is evaluated using the previously described tag-and-probe technique, and dependent on three factors:

Identification: A scale factor is calculated for taus matched at truth-level, for all others this is set to 1.

Electron veto: The efficiency associated to reconstructing taus from electrons which then go onto to pass the BDTElec selection. A scale factor is calculated for taus matched by a truth-level electron, for all others this is set to 1.

Trigger: In this analysis, an $ee/\mu\mu$ pair is required before any $\tau\tau$ pair is sought, hence the trigger scale factor is set to 1.

9.2.5 Pile-up

As described in Section 7.3, at the time of MC production, the modelling of simultaneous proton-proton collisions, or pile-up, occurs in-between simulations of the hard process and detector response. It is only possible to have exact knowledge of the pile-up conditions after data taking is complete, and so the amount simulated will not exactly match that in data. Varying pile-up affects object efficiencies, such as reconstruction and isolation. To correct for the discrepancy, an event weight is applied to MC, which is a function of the average number of interactions per bunch crossing.

9.2.6 The z-position of the primary vertex

The distribution of the z-position of the primary vertex is found to be different in MC compared to data. This may affect the selection of objects, due to the geometric acceptance, on tracks etc., for certain selection criteria. The discrepancy is corrected for by applying an additional event weight to each MC event.

9.2.7 Overall event weight and scaling

An overall event weight is calculated from a product of the above SFs and event weights. It is important to note that even before any corrections are made, some MC sample generators assign an event weight that must also be taken into account. The luminosity of the MC is scaled to match that of the data. Finally, the MC cross-section is scaled by a k-factor to match that of higher order predictions.

9.3 Comparison of data and simulation after di-lepton selection

It is first important to verify that the simulation correctly models the basic kinematics of the di-lepton pre-selection, i.e., the selection of an $ee/\mu\mu$ pair. Figures 9.1, for ee , and 9.2, for $\mu\mu$, compare data and MC distributions after the $Z \rightarrow ee/\mu\mu$ di-lepton pre-selection. A requirement for the the pair invariant mass to lie within a window of $|M_Z - M_{ll}| < 20 \text{ GeV}$ has been applied. Even with the corrections listed in Section 9.2, there are inevitably residual differences. To account for these, the total MC prediction is normalised to the data separately for the $ee/\mu\mu$ channels. The separate normalisation factors are applied respectively to all other $ee/\mu\mu$ di-lepton distributions. In the wider analysis, these $ee/\mu\mu$ normalisation factors make up an additional event weight, applied when an event contains either an ee , $\mu\mu$, or in the case of a four lepton channel (see below) a combination of pairs.

The lower half of each comparison distribution shows the ratio of data to MC. The uncertainty attributed solely to the statistical uncertainty on the data is marked with a cross; the addition of the statistical uncertainty on the MC with a grey band; and finally the systematic uncertainty, calculated by comparing PowhegPythia and Sherpa MC generators (c.f. Section 9.4.1), with a dashed region. All uncertainties are added in quadrature. They are marked separately to allow one to determine the dominant source of uncertainty in each case. For the purposes of this feasibility study, the agreement between data and MC in the di-lepton region is considered adequate.

Other important sets of control distributions are those of the four lepton channels: events containing ee/ee (four electrons), $\mu\mu/\mu\mu$ (four muons) or $ee/\mu\mu$ (two electrons/two muons). Events of this kind (other than background) are only present in the ZZ MC sample. Figure 9.3 shows these. The invariant mass of the leading and sub-leading lepton pairs are shown in a) and b) respectively, and the total invariant mass of the four lepton system in c). By definition, the leading lepton pair has an invariant mass closest to the Z mass. Table 9.1 compares

the number of events measured in data, N_{data} , to those measured in MC, N_{MC} . Overall, there is a general excess observed in the data. This is currently not fully understood and requires further investigation.

Channel	N_{data}	N_{MC}
ee/ee	12 ± 4	7 ± 1
$\mu\mu/\mu\mu$	30 ± 6	21 ± 1
$ee/\mu\mu$	42 ± 7	19 ± 1
Total	84 ± 17	47 ± 3

Table 9.1: Comparison between the number of data and MC events for the four lepton channels. Overall there is a general excess in the data.

9.4 Tau selection parameters

To verify the modelling of the tau selection parameters, a further set of control distributions are made: for each event passing the di-lepton pre-selection, and containing at least one tau that passed the $\tau^{\text{had-vis}}$ selection criteria (c.f. Table 7.3), taus that pass the selection are removed from the event one-after-another. For those remaining the criteria reduced – applying all cuts but one. In total this is done three times, once per selection cut, and a distribution of the ‘but one’ cut variable made. The tau is then replaced and the process repeated. The resulting distributions can be seen in Figure 9.4. Distributions of this kind allow for an unbiased analysis of the data/MC agreement both in and outside the signal region.

9.4.1 Systematic uncertainty

Between PowhegPythia and Sherpa MC samples, there is some disagreement in the modelling of the BDTJet-score, as shown in Figure 9.5 a) and b). In the case of PowhegPythia, the MC under predicts the data, and in the case of Sherpa it over predicts. This has a knock-on-effect into the signal region, as can be seen in Figure 9.5 c) to h), showing the invariant mass of the ee , $\mu\mu$ and $\tau\tau$ pairs. The discrepancy is attributed to the different methods used for next-to-leading order calculations in the two generators, however, its effect is not fully understood. Instead a central MC prediction is obtained by taking a direct average of the PowhegPythia and Sherpa predictions, with systematic uncertainty set to be half the difference between the two. It is hoped in the future this will be reduced with a better understanding of the two generators, in particular with regards to their modelling of the BDTJet-score. Since $ee/\mu\mu$ normalisation factors

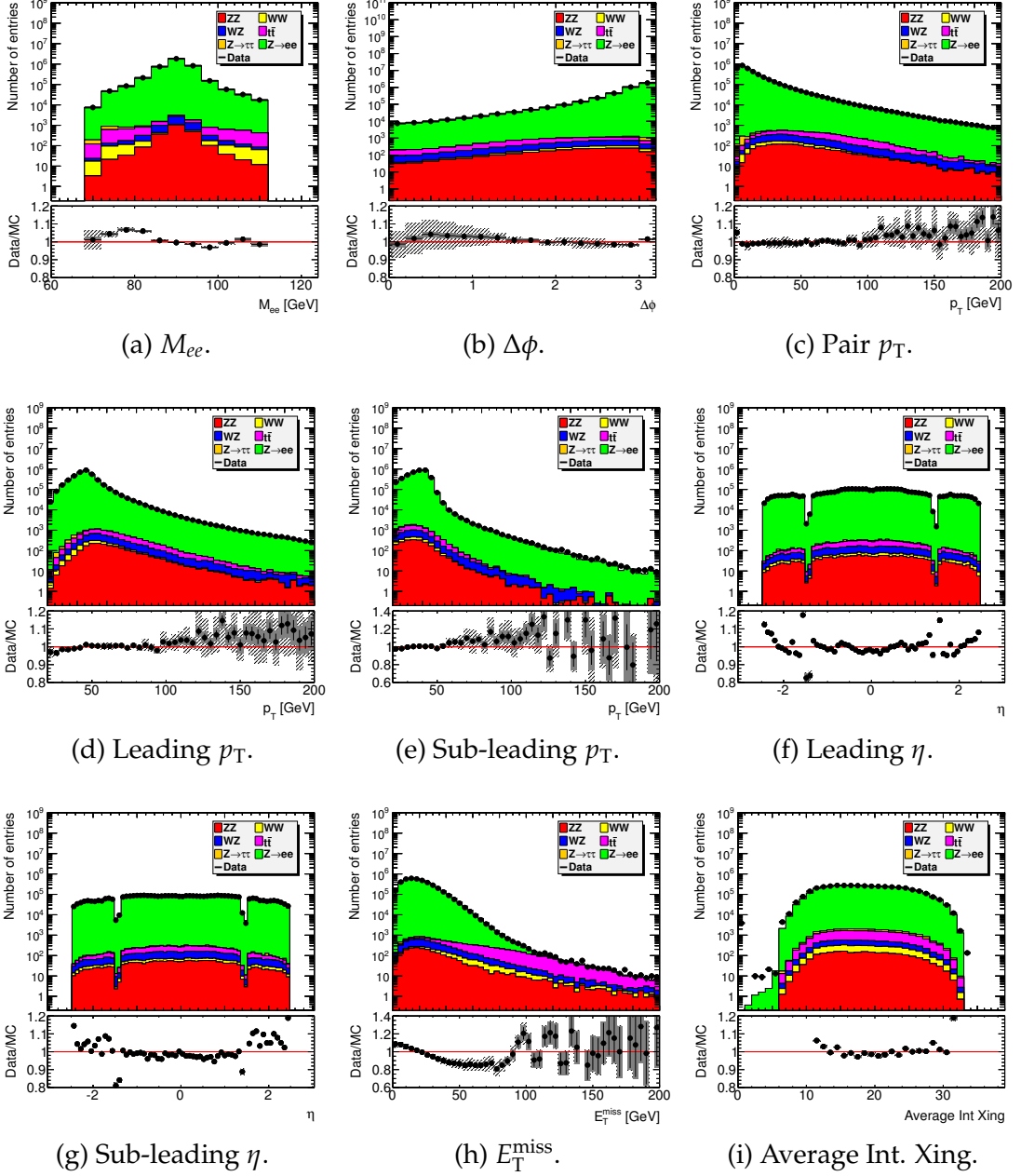


Figure 9.1: Data versus MC for electron pair selection. Figures a) to c) show pair kinematics, d) to g) kinematics for the leading (highest p_T) and sub-leading electron, and h), i) the event E_T^{miss} and average number of interactions per bunch crossing.

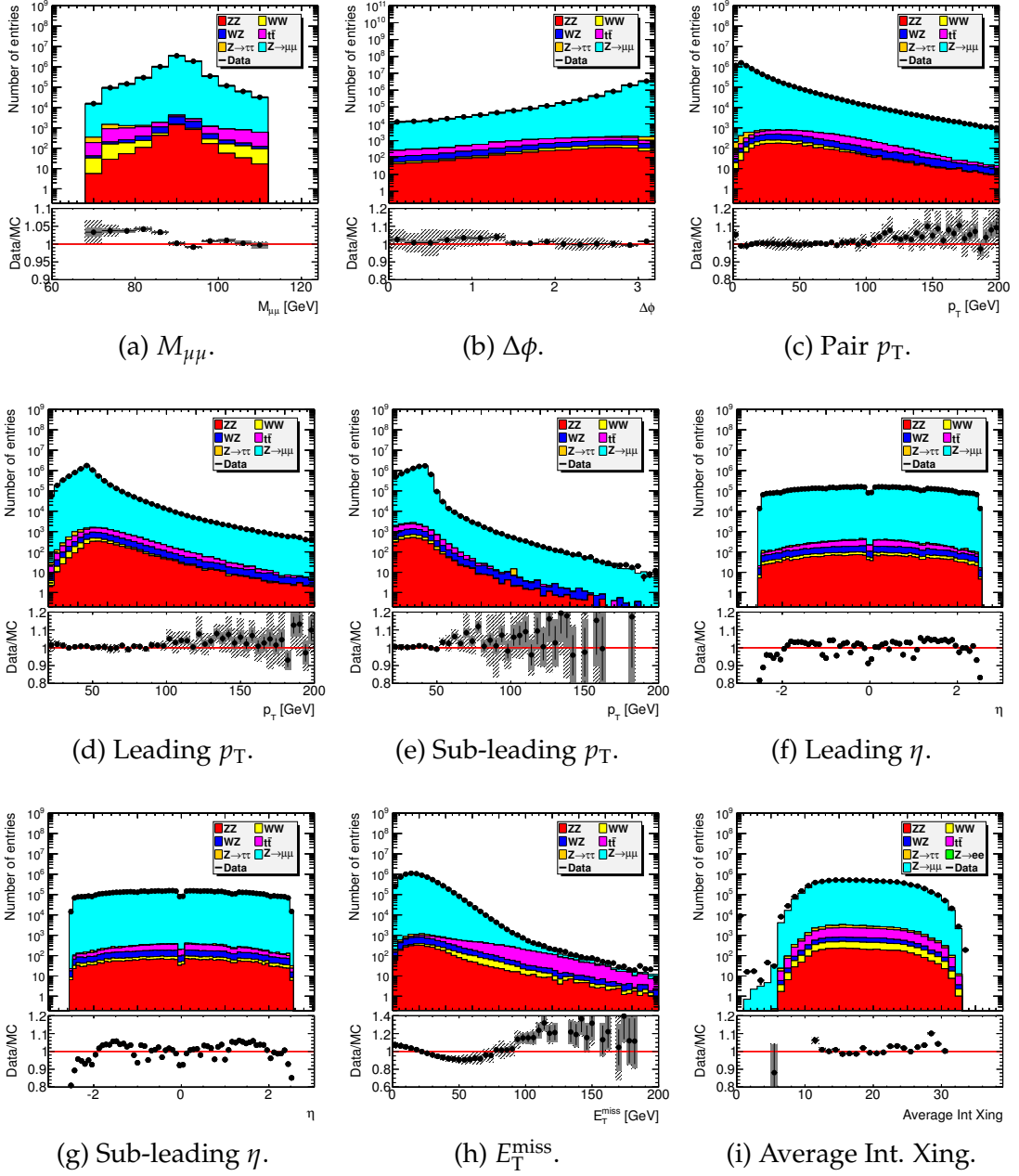


Figure 9.2: Data versus MC for muon pair selection. Figures a) to c) show pair kinematics, d) to g) kinematics for the leading (highest p_T) and sub-leading muon, and h), i) the event E_T^{miss} and average number of interactions per bunch crossing.

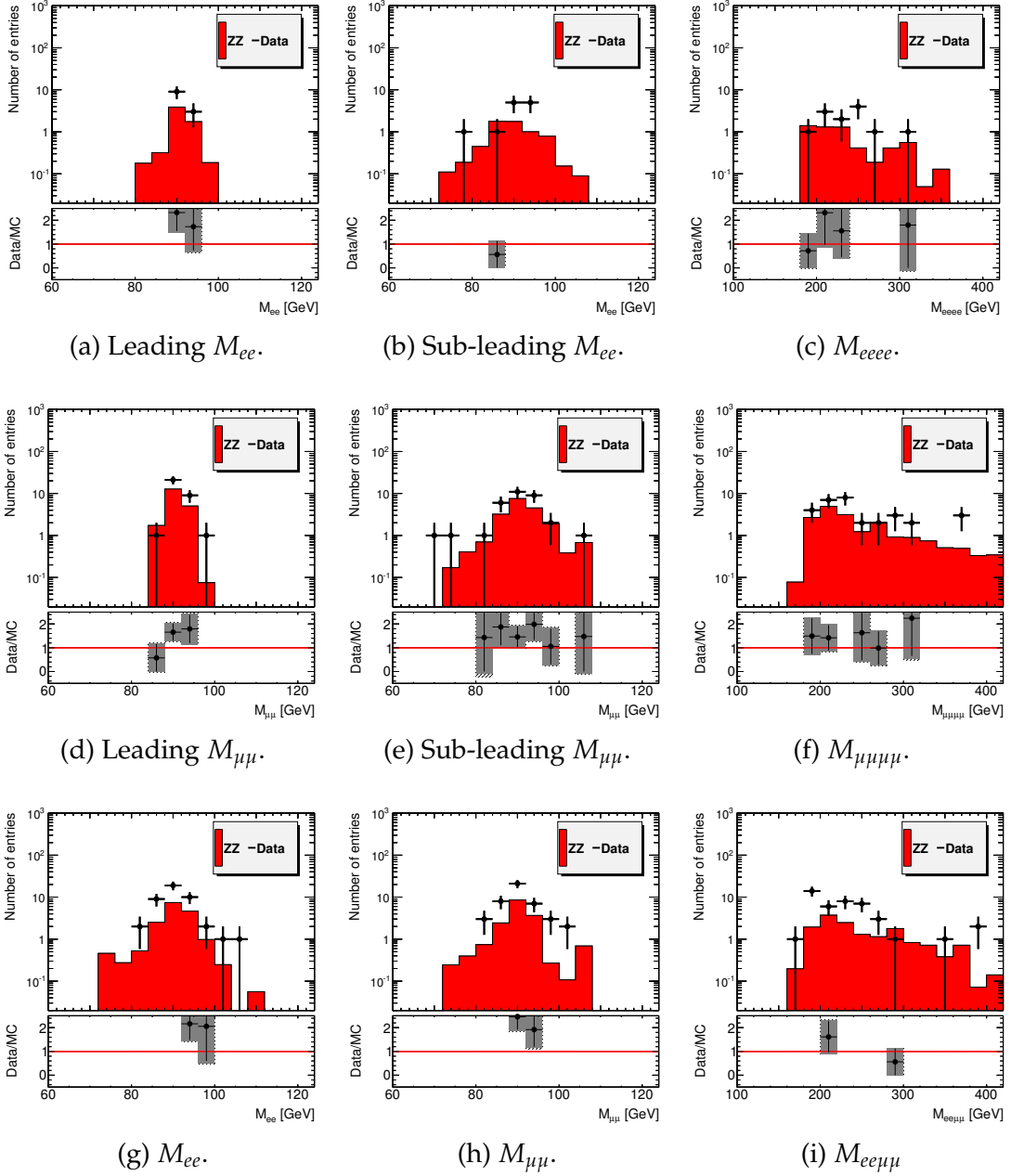


Figure 9.3: Data versus MC for the four lepton channels: a) to c) four electron, d) to f) four muon and g) to i) two electron – two muon. In each row, the right-most figure shows the invariant mass of the four lepton system.

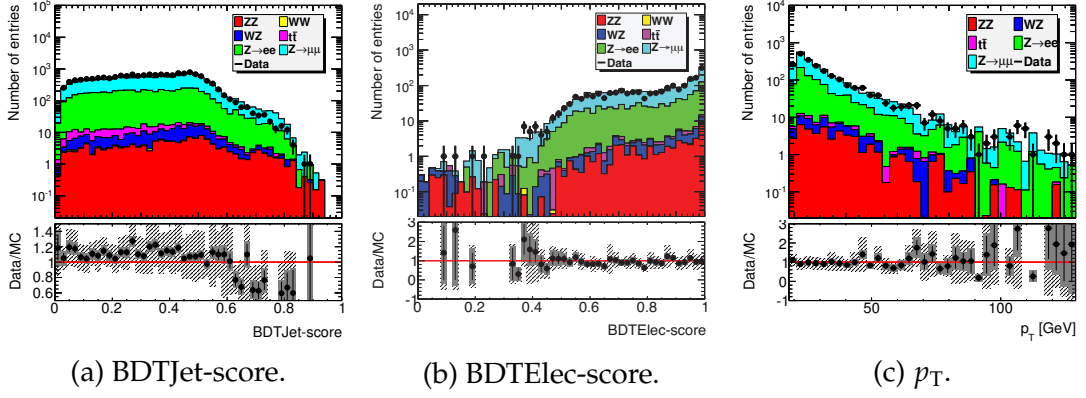


Figure 9.4: Control distributions for the three $\tau^{\text{had-vis}}$ selection parameters: a) the BDTJet-score, b) the BDTElec-score and c) p_T .

make-up an additional event weight (c.f. Section 9.3), there is a corresponding systematic uncertainty attributed to each MC sample containing events that pass the di-lepton selection.

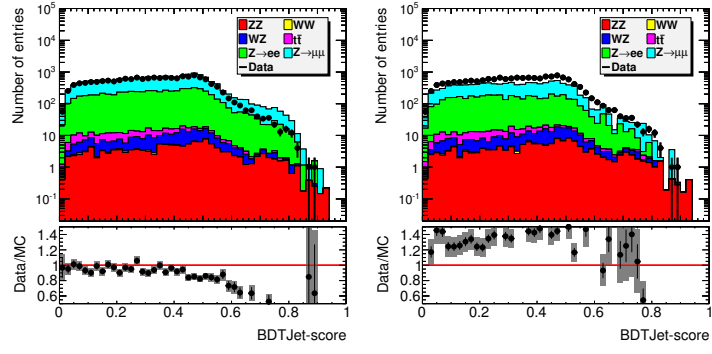
In general there is a systematic uncertainty attributed to each correction described in Section 9.2. However, in this analysis these were found to be less significant than the effect described above, and are not taken into account when calculating the overall systematic uncertainty.

9.4.2 The signal region

Having verified a sufficient agreement between data and MC samples, when taking into account the difference between MC predictions, Figure 9.6 shows control distributions for signal events. By definition these contain a $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ and $Z \rightarrow \tau\tau$ pair, hence the integral of entries in a) and b) is equal to that of c). At this point only single tau selection criteria are applied, with the additional requirement that the charge product of the $\tau\tau$ pair be equal to -1 . This shall be referred to as selection region-1.

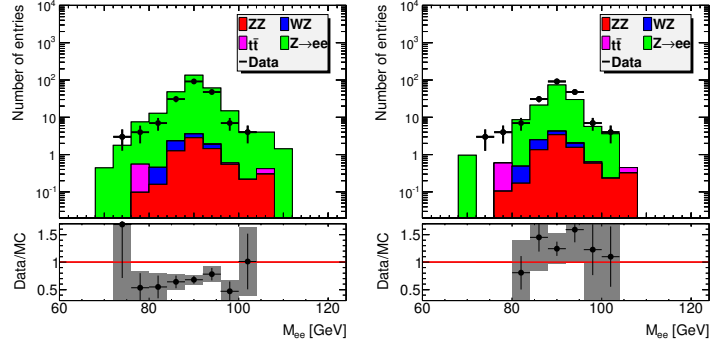
9.5 Tau pair selection

The previous chapter described a method for obtaining additional discrimination against fake events using the $\vec{E}_T^{\text{miss}}$; it was shown that a new parameter, $\Delta\mathcal{E}_T^{\text{miss}}$, improved the discrimination power. Now the performance of other pair parameters are analysed. For all events passing the selection criteria in Table 7.3, Figure 9.7 shows efficiency versus fake rejection, for varying cuts on the tau pair p_T , BDTJet-score sum and BDTElec-score sum. There is a significant deviation from the line of futility in Figure 9.7 c). A cut at 1.2 would retain 85 % of the signal and



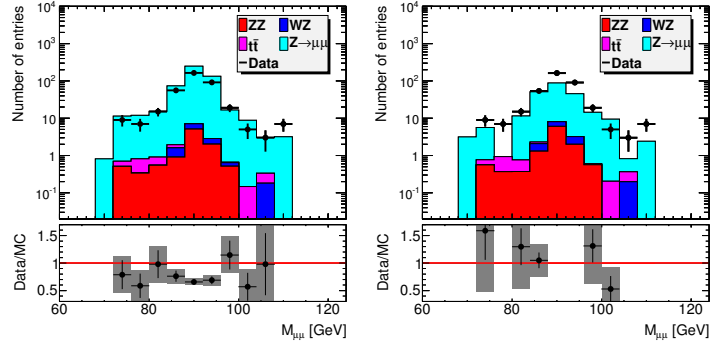
(a) BDTJet-score.

(b) BDTJet-score.



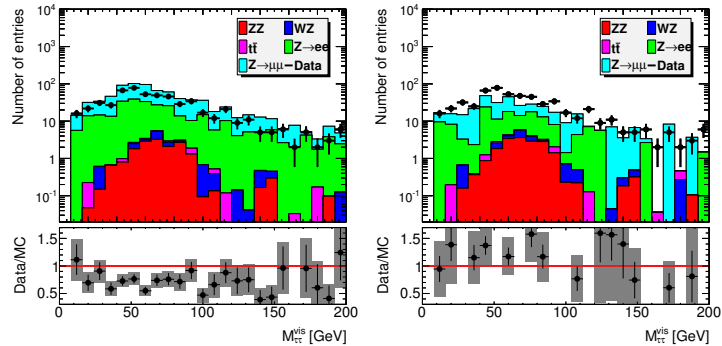
(c) M_{ee} .

(d) M_{ee} .



(e) $M_{\mu\mu}$.

(f) $M_{\mu\mu}$.



(g) $M_{\tau\tau}^{\text{vis}}$.

(h) $M_{\tau\tau}^{\text{vis}}$.

Figure 9.5: Comparison of control distributions using either Sherpa (left) or PowhegPythia (right) samples to describe the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ backgrounds. There is a dramatic difference in the signal region for the BDTJet-score (0.5 to 1) where Sherpa over predicts the data and PowhegPythia under predicts. This has a knock-on-effect for other distributions as can be seen in the M_{ee} , $M_{\mu\mu}$, and the $M_{\tau\tau}^{\text{vis}}$.

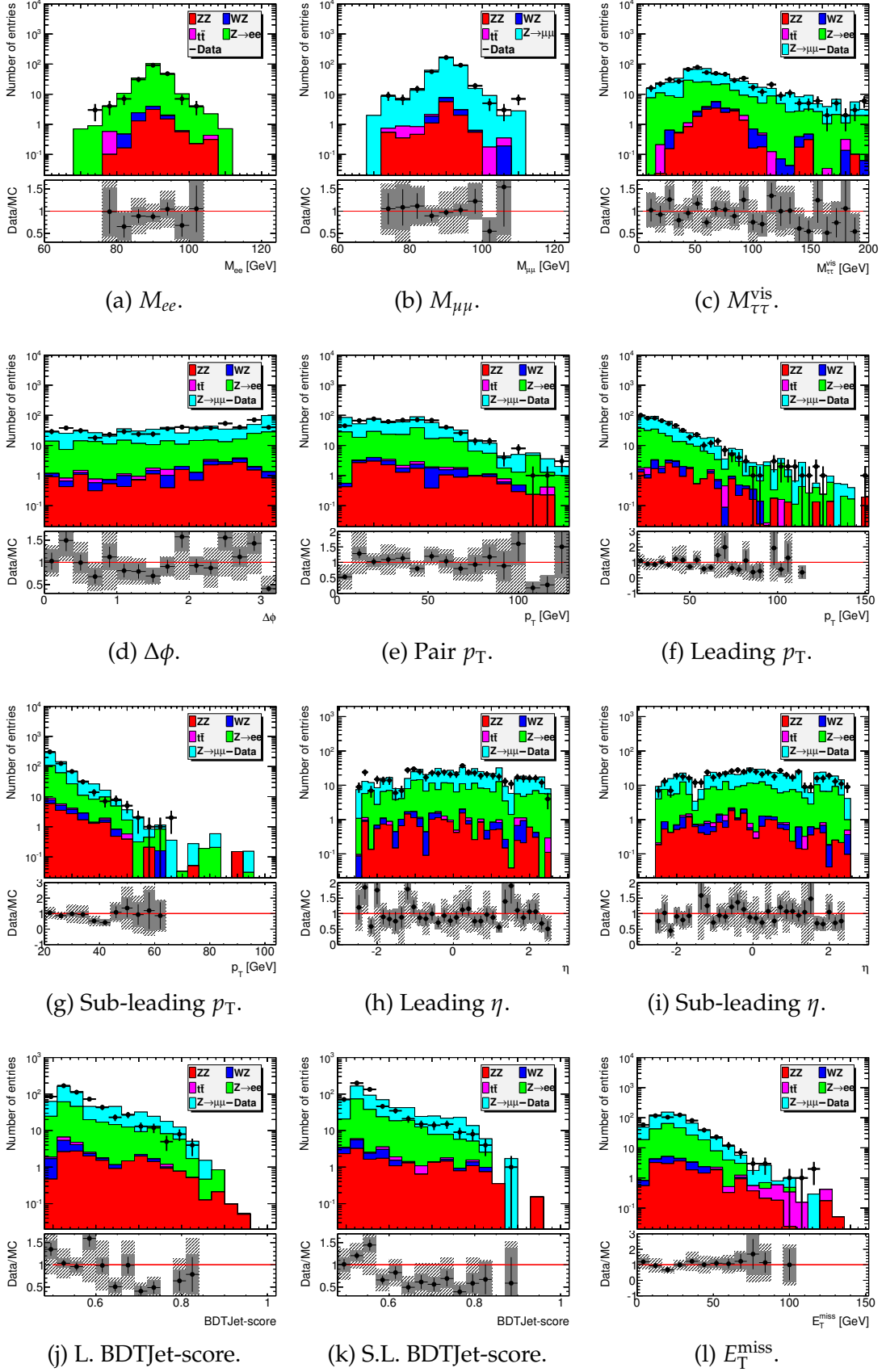


Figure 9.6: Control distributions for signal events ($Z \rightarrow ee/\mu\mu$ and $Z \rightarrow \tau\tau$). The agreement is good given the large systematic uncertainty on the MC. c) to k) refer to $\tau^{\text{had-vis}}$ distributions.

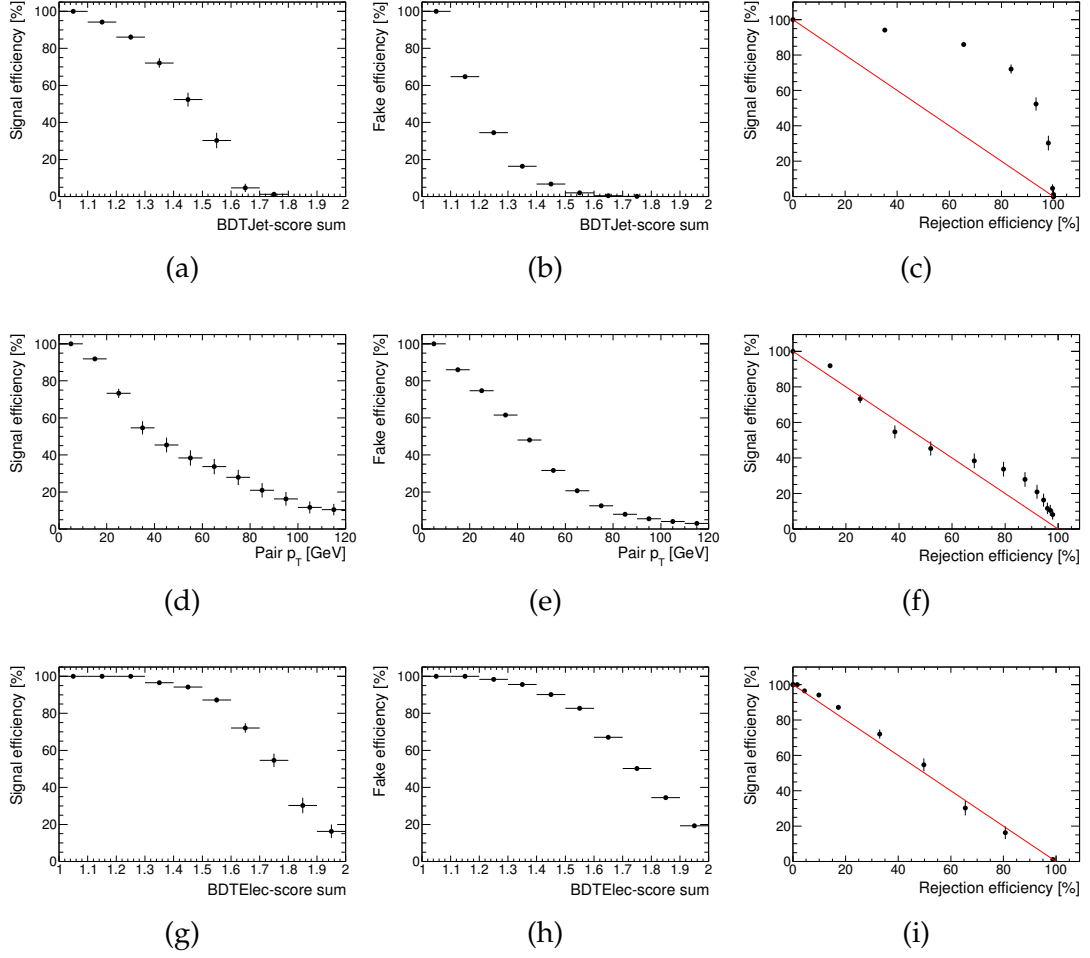


Figure 9.7: Signal efficiency and fake rejection scans comparing additional selection on the tau pair a) to c) BDTJet-score sum, d) to f) p_T , and g) to i) BDTElec-score sum.

remove 66 % of the fakes. No added discrimination is gained from a cut on the pair p_T or BDTElec-score sum. Table 9.2 lists the final event selection, where the additional pair cuts are defined.

9.6 Final selection

Having passed the final event selection, Figure shows comparisons between the data and MC. The general agreement is reasonable, given the large systematic uncertainty on the MC as discussed above. This shall be referred to as selection region-2.

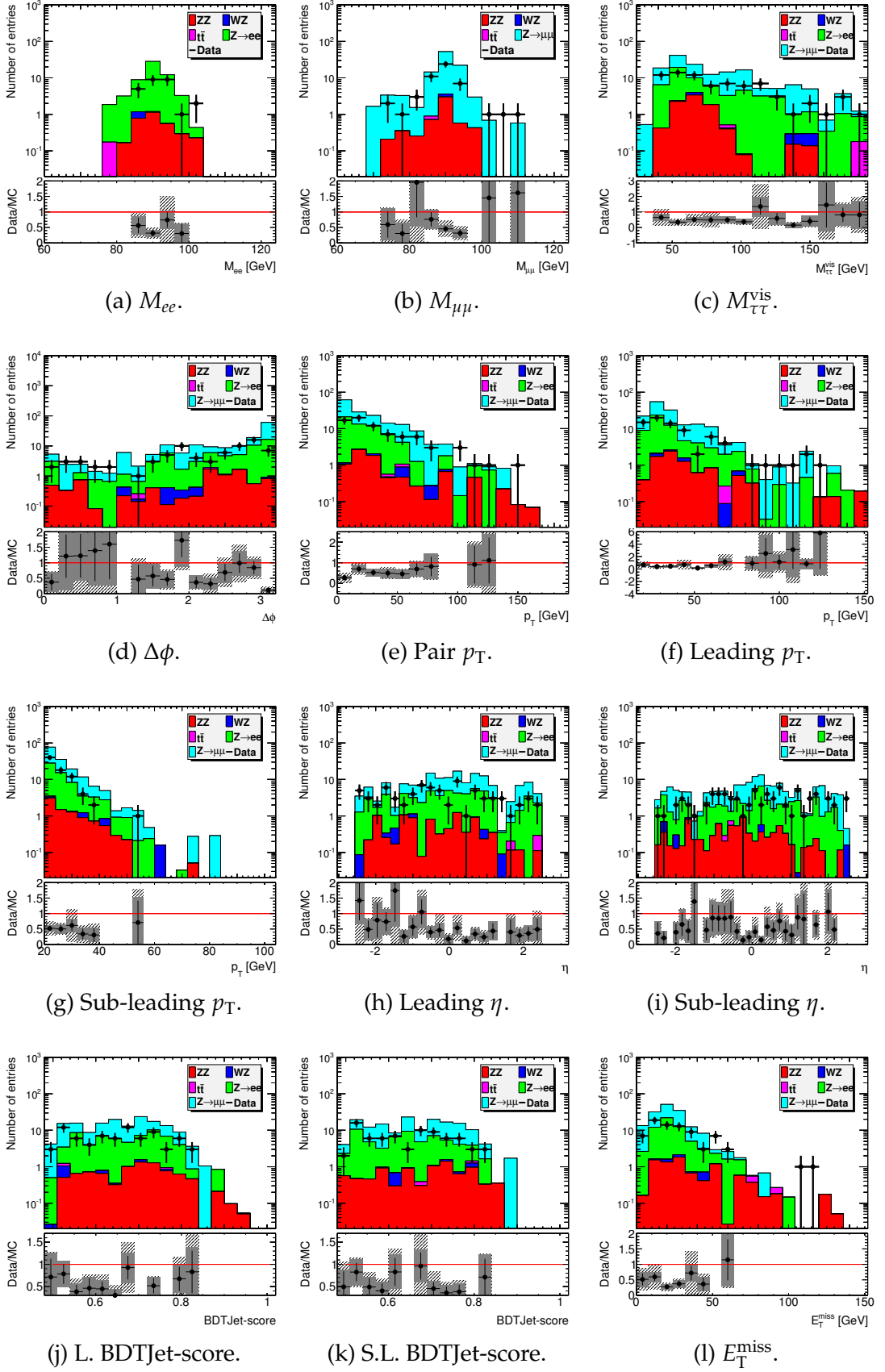


Figure 9.8: Control distributions for the final event selection. c) to k) refer to $\tau^{\text{had-vis}}$ distributions.

Di-lepton pre-selection
single $ee/\mu\mu$ pair with: $ m_{ll} - M_Z < 10 \text{ GeV}$ charge product = -1
$\tau^{\text{had-vis}}$ selection (region-1)
$p_T > 20 \text{ GeV}$ BDTJet-score > 0.5 BDTElec-score > 0.5
$\tau^{\text{had-vis}}$ pair selection (region-2)
single $\tau\tau$ pair with: $\Delta\mathcal{E}_T^{\text{miss}} < 2$ BDTJet-score sum > 1.2 charge product = -1

Table 9.2: Final event selection.

9.7 Results

Assuming the number of background events is well described by poison statistics, a significance value gives a quantitative interpretation of whether the observed number of signal events is statistically significant over the expected fluctuation in background events. It is equal to:

$$\sigma = \frac{N_{\text{signal}}}{\sqrt{N_{\text{background}}}} \quad (9.4)$$

where σ is the significance, N_{signal} the number of signal and $N_{\text{background}}$ the number of background events. Generally a value greater than 3 is deemed to be statistically significant. Table 9.3 lists N_{data} , N_{signal} and $N_{\text{background}}$ as measured from regions 1 and 2. A restriction is placed on the $M_{\tau\tau}^{\text{vis}}$, chosen to remove background-rich/signal-poor upper and lower invariant mass regions, before data, signal and background MC samples are integrated. For region-1 this is: $20 \text{ GeV} < M_{\tau\tau}^{\text{vis}} < 120 \text{ GeV}$, and for region-2: $40 \text{ GeV} < M_{\tau\tau}^{\text{vis}} < 110 \text{ GeV}$. In both cases the significance value is approximately equal to 0.8. Showing that, although the $\tau^{\text{had-vis}}$ pair parameters do provide some additional discrimination power, any benefit is masked by large statistical and systematic uncertainties. A value of 0.8 is not high enough to make the current observation of the $Z \rightarrow ee/\mu\mu$ and $\tau\tau$ channel, where both taus decay hadronically, feasible from the ATLAS 2012 dataset. In region-1, there is reasonable agreement between data and MC, with $N_{\text{data}} = 573 \pm 24$ and $N_{\text{MC}} = 499 \pm 64$, whereas in region-2, there is a slight excess in MC, with $N_{\text{data}} = 77 \pm 9$ and $N_{\text{MC}} = 127 \pm 30$. However, overall, the numbers observed are in line with the expected SM rate.

Selection	Parameter	Value	Error stat.	Error sys.
region-1	N_{data}	573	24	
	N_{signal}	17	4	4
	$N_{\text{background}}$	482	23	33
	σ	0.77		
region-2	N_{data}	77	9	
	N_{signal}	9	3	4
	$N_{\text{background}}$	118	11	12
	σ	0.83		

Table 9.3: Table comparing the number of data, signal and background events present in the two signal regions. A corresponding significance value is listed. Overall the expected number of events measured from the MC is in reasonable agreement with that measured in the data.

9.8 Conclusions

Physics studies at the LHC have allowed for unparalleled observation of di-boson processes, leading to the most accurate cross-section measurements to date. These have focussed on events with electron and muon final states, due to their clean signatures, and high reconstruction, identification and selection efficiencies. With regards to ZZ production, Chapters 7, 8 and 9 focussed on the feasibility of including tau final states, where it was hoped, with the ability to first trigger off a well-defined $Z \rightarrow ee/\mu\mu$ before seeking a $Z \rightarrow \tau\tau$, the number of background events would be greatly reduced. Since e/μ produced in τ^{lep} decays are nearly indistinguishable from prompt e/μ , τ^{lep} are not reconstructed by the ATLAS detector, and the analysis focussed on $Z \rightarrow \tau\tau$ in which both taus decay hadronically. The dominant source of background was, as expected, single Z production and decay to ee or $\mu\mu$ pairs – due to the lepton pair triggering the event selection and fake $\tau^{\text{had-vis}}$ produced by misidentified initial state QCD processes. Through the comparison of MC samples and data taken by the ATLAS detector in 2012, the significance of observing the process was measured to be 0.8, and therefore unlikely to be feasible.

In the high p_T , small $\Delta\phi$ region of interest, $\tau^{\text{had-vis}}$ detection efficiency was shown to improve substantially. At the same time, the correlation between the event E_T^{miss} and $M_{\tau\tau}^{\text{vis}}$, is better defined. This shows promise for future measurements, that are likely to focus on this reduced region, rather than measuring the process inclusively.

As of June 2015, the ATLAS detector has started collecting data for the second major run of its lifetime. The $\sqrt{s}$ has been increased from 8 TeV to 13 TeV, with direct effect on the ZZ and $Z \rightarrow ll$ production cross-sections, as can be seen in

Table 9.4. Both are expected to increase by a factor ~ 2 . With increased $\sqrt{s}$ there is more energy left over from pp collisions for particle boosts in the transverse plane. Hence in this new dataset, a greater fraction of events will likely be in the region of interest, compared to 2012.

Process	σ Theoretical-NLO (nb)	$\sqrt{s}$ (TeV)
ZZ	7.2×10^{-3}	8
	13×10^{-3}	13
$Z \rightarrow ll$	1.12	8
	1.93	13

Table 9.4: Comparison of process cross-sections at different $\sqrt{s}$, [117], [113], [112] and [118].

The bunch-spacing of the LHC beams has been reduced from 50 ns to 25 ns that, along with other modifications, will increase the LHC machine luminosity from $0.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to $2.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [119], [33]. Consequently, at the end of this run in ~ 2018 , the ATLAS detector is expected to have collected an integrated luminosity of $\sim 100 \text{ fb}^{-1}$, and $\sim 300 \text{ fb}^{-1}$ by the end of 2022. This is greater than 10 times the amount of data in the 2012 dataset. Extrapolating from the measured number of signal events in Table 9.4, taking into account the increase in cross-section of signal and background processes and the factor 10 increase in data, one would expect a measurement significance of ~ 3 . Furthermore, since a greater fraction of events will have improved detection efficiency and discrimination power, enhanced further still by the addition of the IBL, the measurement of this process in ATLAS from the current run of the LHC is very likely. However, from the data/MC comparisons made in the final sections of this chapter, there are clearly many improvements that must be made in the modelling of background processes, particularly with regards to the $\tau^{\text{had-vis}}$ BDTJet-score, before any high accuracy measurements can be made.

Chapter 10

Final statement

During 2013/2014, the LHC's machine luminosity was increased. At the same time, several upgrades, including the insertion of the IBL, were carried out on the ATLAS detector in order to maintain its performance over the next data taking run. Besides reducing the adverse effects of increased pile-up, the inclusion of the IBL will enhance the measurement efficiency and accuracy of tracking parameters, many of which are important for object reconstruction in the ATLAS detector. The observation of di-boson ZZ events in which one $Z \rightarrow ee/\mu\mu$ and the other $Z \rightarrow \tau\tau$, will benefit from this, in addition to the increased luminosity, propelling it into the sensitivity range of the ATLAS detector.

One of the main issues with regards to placing detectors so close to the interaction point is the large increase in radiation fluence. This damages and degrades the amount of signal collected from a traversing particle. Having been included in the IBL, 3D silicon is a strong candidate for future pixel detector upgrades. Adopting the 3D principle in diamond could result in an ultra-radiation tolerant detector. The technique of fabricating electrodes with a laser, allows for low cost rapid prototyping of new designs and ideas.

In order to exploit the LHC to its full potential, a high luminosity upgrade is planned after 2022 – the HL-LHC. It will allow for unprecedented precision measurements to test the validity of the Standard Model. However, for it to be a success, the continued R&D of ultra-radiation tolerant detectors, such as those described in this thesis, is essential.

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