Search for heavy neutral leptons using displaced vertices in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Abstract

The observation of neutrino oscillations implies that neutrinos have non-zero masses. Although the Standard Model (SM) of particle physics describes the behaviors of elementary particles and their interactions precisely, it does not explain the origin of the neutrino masses. Several theories have been proposed so far to explain the origin of the small neutrino masses, and among them, an extension of the SM by adding three right-handed neutrinos is an attractive proposition. These newly introduced right-handed neutrinos are also referred as “sterile neutrinos” or “heavy neutral leptons (HNLs)”. In these models, the small neutrino masses are assured by the seesaw mechanism, while the lightest HNL can be a candidate for dark matter. If the remaining two HNLs have smaller masses than the electroweak scale, it could explain the baryon asymmetry in the universe. This model which can address outstanding issues in the SM was examined by the DELPHI experiment at the Large Electron-Positron collider (LEP) in the 1990s. The experiment set a constraint on the strength of the coupling between the muon neutrino and the HNL, i.e., $|U_{\mu N}|^2$, of approximately $10^{-5}$. This upper limit has not been updated for 20 years, and it is crucial to perform a more sensitive search for the HNLs.

For this purpose, the HNLs are searched for using proton-proton collision data collected from the ATLAS detector at the Large Hadron Collider (LHC). The data were collected in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 32.9 fb$^{-1}$. The HNLs with masses between sub-GeV and tens of GeV can be produced via $Z$ bosons or $W$ bosons, and the data includes approximately $10^9$ of $W$ bosons produced at the proton-proton collisions. This $W$ boson rich environment allows us to perform a very sensitive search for the HNLs.

The HNLs are assumed to have relatively long lifetimes due to their weak couplings with the SM particles and displace the vertices from the collision point in the ATLAS detector. Tracks from the HNLs’ vertices are not reconstructed by the ATLAS standard tracking procedure, which assumes that the tracks originate from the collision point. In this study, a dedicated method is developed to reconstruct the tracks from displaced vertices (DVs).

A final state of the HNLs reconstructed in the ATLAS detector may include a muon from the $W$ boson decay and a displaced vertex (DV) composed of two leptons (either $\mu\mu$ or $\mu e$) as the decay products of HNLs. The prompt muon from the $W$ boson decay is used for trigger. One remarkable feature of this analysis is the extremely small number of backgrounds. This is because there is no irreducible background process in the SM where a particle decays to a charged lepton pair at a macroscopic distance. The decay products of $J/\psi$ and $\psi(2S)$ from $B$ hadrons can make a DV with two charged leptons; however, it has been verified that requiring an invariant mass of the DV to be larger than 4 GeV can completely remove such background events. Cosmic muons traveling close to the collision point could be reconstructed as a muon pair vertex, and this could be a source of background events. However, such events can be rejected using their “back-to-back” topology. The DVs made by a random coincidence of charged leptons from pileup events are estimated by a data-driven method. The upper limit of the background events in our signal region is estimated to be 2.3 at 90% confidence level. No event is observed in the signal region. The search sets the current best constraint on the strength of $|U_{\mu N}|^2$ to the order of $10^{-6}$ for an HNL mass in the range of 5 GeV to 9 GeV.
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Chapter 1

Introduction

The ultimate theory of particle physics should be able to answer fundamental questions such as “What is the universe made of?”. The theory would describe the elementary particles which constitute the universe and their interactions. Unfortunately, we have not yet obtained such a theory. We still do not know how many kinds of elementary particles are there in the universe. Although we are a long way from achieving the ultimate theory, there have been many progresses over the past few decades. The Standard Model (SM) of the particle physics has been partly successful in playing the role of the ultimate theory. The SM describes three out of the four known fundamental interactions, and all the particles in the SM have been already discovered by the enormous efforts of the scientific community. However, it is a fact that some phenomena cannot be explained in the framework of the SM despite its great success. The observations of neutrino oscillations, dark matter, and baryon asymmetry in the universe are examples of such phenomena. For this reason, our immediate concern is to expand the SM in a manner being consistent with the existing observations and verifying newly suggested theories. Although a number of elegant theories have been proposed so far, we have not obtained satisfactory results as mentioned above. It is important to keep examining the new expansions of the SM. In this thesis, we focus on the fact that a neutrino in the SM should have its chiral partner to explain its mass. Moreover, we examine one of the expansions of the SM in which three right-handed neutrinos are introduced. The right-handed neutrino is searched for with the powerful apparatus, A Toroidal LHC ApparatuS (ATLAS), at the Large Hadron Collider (LHC) to study the physics beyond the SM.

Outline of the thesis

In the initial chapters of this thesis, the theoretical backgrounds, experimental apparatus, procedure of object reconstruction, and physics simulations are discussed.

- Chapter 2 provides a theoretical background to motivate this study. The outline of the SM and its outstanding issues are briefly reviewed. An elegant theory which can solve these issues is mentioned, and the possibility of an experimental search for it is also discussed.
- Chapter 3 presents an overview of the experimental apparatus for this study.
- Chapter 4 outlines the method of event simulation and the setup used in the analysis.
- Chapter 5 describes the reconstruction procedure for physics objects with collected data.
In the later chapters, the detailed analyses are presented.

- Chapter 6 presents the event selections and region definitions for the analysis.
- Chapter 7 describes the data-driven background estimation method adopted in this analysis.
- Chapter 8 presents an overview and evaluates the systematic uncertainties associated with background estimation.
- Chapter 9 shows the results and resultant limits.

Finally, in the last chapter, a conclusion of this study is presented.
Chapter 2
Theoretical Background

The aims of elementary particle physics include revealing the elemental particles and elucidating their interactions. In this chapter, an outline of the Standard Model (SM) of particle physics which can explain most of the phenomena in nature is presented, and its outstanding issues are reviewed. An extension of the SM to address these issues is also discussed.

2.1 The Standard Model of Particle Physics

There are four fundamental interactions: gravitational, electromagnetic, weak, and strong interactions. The SM describes three of them, except gravitational interaction. In other words, it represents the behavior and interactions of the quarks and leptons shown in Fig. 2.1 in the framework of the gauge theory based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry.

Quarks are spin-1/2 fermions, which interact via the strong, weak, and electromagnetic interactions, while the fermions with spin of 1/2 which are not influenced by strong interactions are called “leptons”. In particular, neutral leptons are called “neutrinos” and appear only with left-handed chirality as shown in Fig. 2.1. In the gauge theory, massless spin-1 gauge bosons are generated as a consequence of the gauge symmetry, and they mediate the interactions between matter particles such as leptons and quarks as well as the gauge bosons themselves. $SU(3)_C$ represents the symmetry of strong interactions and its gauge boson is called “gluon”. Strong interactions are characterized by color charge, and the quarks involved in such interactions are treated as color triplets of $SU(3)_C$. The theory that describes strong interactions is called quantum chromodynamics (QCD). The symmetry of electromagnetic interactions is expressed by $U(1)_{EM}$, and the “photon” plays the role of the gauge boson. Weak interactions could not be described in the framework of the gauge theory. In the beta decay, which is a typical phenomenon caused by weak interactions, the mediator must have a finite mass although the mass of a gauge boson is strictly prohibited by the gauge symmetry. Glashow, Salam, and Weinberg proposed the unification of electromagnetic and weak interactions in the late 1960s [1–4] as electroweak interactions and described them with $SU(2)_L \times U(1)_Y$. The quantum numbers, denoted by $SU(2)_L$ and $U(1)_Y$, are referred to as the weak isospin and the weak hyper-charge, respectively. In 1964, Englert, Brout, Higgs, Guralnik, Hagen, and Kibble suggested the possibility of a boson acquiring the mass consistent with the gauge invariance by applying a spontaneous symmetry breaking to the gauge theory [5–7]. A spin-0 scalar field, introduced in the theory as Higgs field, can trigger the spontaneous symmetry breaking. $SU(2)_L \times U(1)_Y$ symmetry is broken spontaneously by the spin-0
2.1. THE STANDARD MODEL OF PARTICLE PHYSICS

Higgs field and only the $U(1)_{EM}$ gauge symmetry remains. $SU(2)_L$ and $U(1)_Y$ have three gauge bosons and one gauge boson, respectively. The process by which the gauge bosons acquire finite masses is called “Higgs mechanism”. The gauge symmetry is broken by the Higgs field having a vacuum expectation value. Three out of the four gauge bosons, $W^\pm$ and $Z$ bosons, acquire masses and mediate the weak interactions. The remaining gauge symmetry, $U(1)_{EM}$, describes the electromagnetic interactions, and its gauge boson corresponds to the massless photon. The combination of this theory and QCD is called the SM.

2.1.1 The Standard Model Lagrangian and Fermion Masses

A spin-1/2 fermion $\psi$, generally, has four components in the Dirac theory. If one chooses an appropriate basis for $\psi$, it can be divided into a left-handed fermion $\psi_L$ and a right-handed fermion $\psi_R$ each having two components. These have eigenvalues of $\mp 1$ for the $\gamma_5$ matrix given by

$$\gamma_5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3, \quad \gamma_5^\dagger = \gamma_5,$$

where $\gamma^\mu$ denotes the $\gamma$ matrix in the Dirac theory. The operators defined as

$$P_L \equiv \frac{1 - \gamma_5}{2}, \quad P_R \equiv \frac{1 + \gamma_5}{2}$$

are called projection operators and satisfy the following relations:

$$P_L + P_R = 1, \quad P_L^2 = P_L, \quad P_R^2 = P_R, \quad P_LP_R = P_RP_L = 0.$$
Using \( P_L \) and \( P_R \), \( \psi_L \) and \( \psi_R \) are defined by

\[
\psi_L \equiv P_L \psi, \quad \psi_R \equiv P_R \psi. \tag{2.4}
\]

The Dirac conjugations \( \bar{\psi}_L \) and \( \bar{\psi}_R \) are described using the relations \( \gamma_5^\dagger = \gamma_5 \) and \( \{ \gamma^\mu, \gamma_5 \} = 0 \) as follows:

\[
\bar{\psi}_L = \psi_L^\dagger \gamma^0 = (P_L \psi)^\dagger \gamma^0 = \psi_L^\dagger P_L \gamma^0 = \bar{\psi}_R,
\]

\[
\bar{\psi}_R = \bar{\psi} P_L. \tag{2.5}
\]

Therefore, the Lagrangian \( \mathcal{L} \) for a free fermion \( \psi \) is defined as

\[
\mathcal{L} \equiv i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi = \mathcal{L}_{\text{kin}} + \mathcal{L}_m, \tag{2.7}
\]

where the kinetic term \( \mathcal{L}_{\text{kin}} \) can be written as

\[
\mathcal{L}_{\text{kin}} = i \bar{\psi} \gamma^\mu \partial_\mu \psi = \bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R \gamma^\mu \partial_\mu \psi_R, \tag{2.8}
\]

and \( \psi_L \) and \( \psi_R \) construct the kinetic term independently. On the other hand, the mass term \( \mathcal{L}_m \) becomes

\[
- \mathcal{L}_m = m \bar{\psi} \psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L), \tag{2.9}
\]

where \( \psi_L \) and \( \psi_R \) cannot be separated. The SM assigns different quantum numbers to the left-handed and right-handed fermions under \( SU(2)_L \times U(1)_Y \) gauge symmetry. This means that the SM treats the left-handed electron (\( e_L \)) and the right-handed electron (\( e_R \)) as different particles. Under \( U(1)_{EM} \) gauge symmetry, the electric charges of the left-handed and right-handed electrons are identical such that the mass term is gauge-invariant under the \( U(1)_{EM} \) gauge transformation \( e \rightarrow e' \). On the other hand, if the weak hypercharges, \( Y_R \) and \( Y_L \), are different between \( e_R \) and \( e_L \), the mass term is transformed under \( U(1)_Y \) gauge transformation as

\[
- \mathcal{L}_m = m e_R e'_L = m e^{-i(Y_R-Y_L)\theta} e_Re_L \neq e_Re_L, \tag{2.10}
\]

where \( \theta \) is a transform parameter. In this case, the mass term breaks the \( U(1)_Y \) gauge invariance. In the SM, the fermions are massless due to the gauge symmetry, and their masses are given by the spontaneous breaking of \( SU(2)_L \times U(1)_Y \) symmetry to \( U(1)_{EM} \) symmetry.

The SM Lagrangian consists of the following: kinetic terms of the gauge bosons, the fermions, and the Higgs field (\( \mathcal{L}_{\text{kin}} \)); the Yukawa interaction term (\( \mathcal{L}_{\text{Yukawa}} \)) which describes the interaction between the spin-1/2 fermion field and the scalar field; and the scalar potential from the self-interaction of the Higgs field (\( V_{\text{Higgs}} \)).

\[
\mathcal{L}_{SM} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{Yukawa}} - V_{\text{Higgs}} \tag{2.11}
\]

The kinetic term \( \mathcal{L}_{\text{kin}} \) is given by

\[
\mathcal{L}_{\text{kin}} = -\frac{1}{4} \sum_{a=1}^{8} G_{\mu\nu}^a G^{\mu\nu}_a - \frac{1}{4} \sum_{a=1}^{3} W_{\mu\nu}^a W^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \bar{\psi}_L \gamma^\mu D_\mu \psi_L + i \bar{\psi}_R \gamma^\mu D_\mu \psi_R + |D_\mu \phi|^2, \tag{2.12}
\]

where the first three terms describe the kinetic terms of \( SU(3)_C, SU(2)_L, \) and \( U(1)_Y \) gauge fields, respectively, and the covariant differential \( D_\mu \) is expressed as

\[
D_\mu = \partial_\mu + ig_s \frac{\lambda^a}{2} G_\mu^a + ig \frac{\sigma^a}{2} W_\mu^a + ig Y B_\mu. \tag{2.13}
\]
The Lagrangian of Yukawa interaction is written as

\[- \mathcal{L}_{\text{Yukawa}} = f_u \bar{q}_u R \phi^c + f_d \bar{q}_d R \phi + f_e \bar{e}_L R \phi + h.c., \]

(2.14)

where \( h.c. \) represents the Hermitian conjugate. The Higgs potential is given by

\[ V_{\text{Higgs}} = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \left( \mu^2 < 0, \; \lambda > 0 \right). \]

(2.15)

The fermions acquire their masses from the Higgs field \( \phi \) with the vacuum expectation value \( v \) given by

\[ \phi = \left( \begin{array}{c} 0 \\ v \end{array} \right), \; v^2 = -\frac{\mu^2}{\lambda} \]

(2.16)
in Eq. (2.14). For the masses of leptons,

\[- \mathcal{L}_{\text{Yukawa}} = f_e \bar{e}_L R \phi + h.c. \]

\[ = f_e (\bar{\nu}_e \bar{e}_L) e_R \left( 0, \; \frac{v}{\sqrt{2}} \right)^T + h.c. \]

\[ = f_e \frac{v}{\sqrt{2}} \bar{\nu}_e L e_R + h.c. \]

(2.17)

Comparing with Eq. (2.9), the electron mass is given by

\[ m_e = f_e \frac{v}{\sqrt{2}} \]

(2.18)

### 2.2 Outstanding Issues in the Standard Model

Despite of its enormous success, there are some experimental results which cannot be explained in the framework of the SM. In this section, some of the outstanding issues in the SM are discussed.

#### 2.2.1 Neutrino Masses

The observation of neutrino oscillations [8, 9] implies that a neutrino has a non-zero mass \((< \mathcal{O}(10^{-1}) \text{ eV})\). However, in the mass term of the SM Lagrangian, left- and right-chiralities appear simultaneously and there is no right-handed neutrino. Therefore, a neutrino cannot have a non-zero mass in the SM.

#### 2.2.2 Dark Matter

In the 1930s, Zwicky pointed out that the mass of visible galaxies cannot be explained by the mass calculated from the velocity dispersion of the galaxies by applying the virial theorem to the Coma cluster [10]. Moreover, Babcock also observed that the rotation speed of the fringe area is much faster than that expected from the visible mass by measuring the rotation curves of the Andromeda nebula [11]. In the 1970s, further measurements of the galaxy rotation curves were performed, and it was revealed that the rotation speed becomes constant and independent from the distance in the fringe area. Thus, there is a vast amount of matter generating gravity in the fringe area, even if it is invisible. This is referred to as “dark matter”. In recent years, measurements with the Bullet cluster, Wilkinson Microwave Anisotropy Probe (WMAP) satellite, Planck satellite, etc. have also supported the existence of dark matter [12, 13].
2.2.3 Baryon Asymmetry in the Universe

Everything in the universe is made of matter. If the universe is symmetric with respect to matter and antimatter, there must be the same number of antimatter particles in the universe as that of matter. The asymmetry between the matter and antimatter in the universe is often referred to as “baryon asymmetry in the universe (BAU)”. A possible explanation for this asymmetry is that the baryons remain from coannihilation with antibaryons when they get out of the thermal equilibrium, and the number of baryons and antibaryons are frozen out. However, the number of baryons produced by such a process is too small to explain the baryons remaining in the current universe. Therefore, it is necessary that at the beginning of the universe, there must have been an asymmetry with respect to the baryons and antibaryons. To accomplish the asymmetry, there are some requirements known as “Sakharov conditions” [14]:

1. baryon number violation,
2. C-symmetry and CP-symmetry violation, and
3. interactions out of thermal equilibrium.

The necessity of the first condition is obvious. The second condition is necessary because if one applies C- or CP-transformation to a baryon-number violating reaction, it will make the same amount of antibaryons as the amount of baryons produced by the original reaction. Therefore, even if the process which violates baryon number exists, the net baryon number is unchanged. Finally, under the thermal equilibrium, CPT symmetry assures an inverted reaction at the same rate. Indeed, the process increasing the baryon number and the process decreasing the baryon number are balanced, and the generated baryon asymmetry is washed out. Therefore, the third condition is also necessary. All interactions where the reaction rates are less than the expansion coefficient of the universe can fulfill the third condition. However, the interactions which violate the baryon number and CP-symmetry are unable to explain the baryon asymmetry in the SM. Thus, another process which satisfies both the conditions is desired.

2.3 Heavy Neutral Lepton

The minimal extension of the SM to explain the small neutrino masses is just the addition of right-handed neutrinos to the SM. Such a neutrino is also referred to as a “sterile neutrino” or a “heavy neutral lepton (HNL)”. In this section, a physics model which can explain the neutrino mass as well as giving a candidate of the dark matter and baryon asymmetry is reviewed.

2.3.1 Seesaw Mechanism

We know that neutrinos have minute masses, although they are treated as massless in the SM. This is because the SM is constructed in such a manner considering the absence of right-handed neutrinos and there is no rationale of being massless. This situation differs from photons and gluons which are required to be massless by gauge symmetry. It is easy to introduce neutrino masses in the SM. If three right-handed neutrinos which do not experience any interactions in the SM are introduced, the neutrinos can get their masses from Yukawa interactions with the left-handed neutrinos in the same way as the quarks in the SM referred to as the “Dirac mass”:

$$ -\mathcal{L}_D = m_D \bar{\nu}_L \nu_R + m_D \bar{\nu}_R \nu_L. $$

(2.19)
Figure 2.2: Expansion of the Standard Model.

However, in this approach, the reason why the neutrinos have much smaller masses than other fermions is not explained. Since neutrinos do not have electric charges, neutrinos cannot just be Dirac fermions but also Majorana fermions. If a neutrino is a Majorana particle, it can also have Majorana mass:

\[-L_M = M_M \bar{\nu}_R \nu_R + m_D \bar{\nu}_L \nu_L^C,\]  

where \(\nu^C\) represents a charge conjugation of \(\nu\). The seesaw mechanism can provide an explanation for the small neutrino masses [15–18]. If the Dirac mass between \(\nu_L\) and \(\nu_R\) is \(m_D\) and the Majorana masses of \(\nu_R\) and \(\nu_L\) are \(M_M\) and 0, respectively, the neutrino mass term can be written as follows:

\[
(\bar{\nu}_L, \bar{\nu}_R^C) \left( \begin{array}{cc} 0 & m_D \\ m_D & M_M \end{array} \right) \left( \begin{array}{c} \nu_L^C \\ \nu_R \end{array} \right) + (\bar{\nu}_L, \bar{\nu}_R) \left( \begin{array}{cc} 0 & m_D \\ m_D & M_M \end{array} \right) \left( \begin{array}{c} \nu_L \\ \nu_R^C \end{array} \right).
\]  

Diagonalizing the \(2 \times 2\) matrix \(M\), the eigenvalues are \(-m_D^2/M_M\) and \(M_M\) for \(m_D \ll M_M\).

### 2.3.2 Introduction to the Neutrino Minimal Standard Model (\(\nu\)MSM)

As discussed, the addition of right-handed neutrinos to the SM can explain the small neutrino masses. In most models which incorporate the seesaw mechanism, the eigenvalues of \(M\) are much larger than the scale of electroweak symmetry breaking. Instead of introducing such a new energy scale, the model considered here introduces three right-handed neutrinos to be equal to the number of generations of fermions with a mass smaller than the electroweak scale as shown in Fig. 2.2. This model is called the neutrino minimal Standard Model (\(\nu\)MSM) [19], in which the three newly introduced right-handed neutrinos are singlet under all gauge interactions. The Yukawa couplings
of the sterile neutrinos are very small due to their relatively smaller masses, and two of them \((N_2 \text{ and } N_3)\) degenerate to explain the baryon asymmetry in the universe (BAU) and production of dark matter simultaneously. The lightest one \((N_1)\) can be a candidate for dark matter. The model is described by the following Lagrangian:

\[
\mathcal{L}_{\nu_{\text{MSM}}} = \mathcal{L}_{\text{SM}} + \bar{\nu}_R \phi \nu_R - \bar{L}_L F \nu_R \Phi - \bar{\nu}_R F^\dagger L_L \Phi^\dagger - \frac{1}{2} (\bar{\nu}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^C). \tag{2.22}
\]

\(\mathcal{L}_{\text{SM}}\) is the Lagrangian of the SM, \(F\) is a matrix of Yukawa couplings, and \(M_M\) is a Majorana mass term for the right-handed neutrinos \(\nu_R\). \(L_L = (\nu_L, e_L)^T\) are left-handed lepton doublets in the SM, and \(\Phi\) is the Higgs doublet. \(\phi\) denotes \(\gamma^\mu \partial_\mu\). This Lagrangian is well-known in the context of the seesaw mechanism for neutrino masses and leptogenesis.

In the \(\nu_{\text{MSM}},\) neutrino masses are generated from the Dirac masses \(m_D = F v\) and the Majorana masses \(M_M\) by the seesaw mechanism (\(v\) is the Higgs vacuum expectation value) briefly described in Sec. 2.3.1. In the limit \(M_M \gg m_D,\) there are two distinct sets of neutrino mass eigenstates. The mass matrices for active and sterile neutrinos are obtained by the block diagonalization of the full mass matrix. These are expressed as \(m_{\nu} = -\theta M_M \theta^T\) and \(M_N = M_M + \frac{1}{2} \theta^\dagger \theta M_M \theta^T\) \(\theta^*\) for active and sterile neutrinos, respectively. These are not diagonal to cause neutrino oscillations. Here, the matrix \(\theta\) with the component of \(\theta_{\alpha I} = (m_D M_M^{-1})_{\alpha I}\) determines the active-sterile mixing angle. The active mass eigenstates \(\nu_i\) with masses \(m_i\) are mainly the mixings of the SM neutrinos \(\nu_{L,\alpha}\), while the remaining three sterile neutrinos \(N_I\) with masses \(M_I\) are mainly the mixings of right-handed neutrinos \(\nu_{R,I}\). The sterile neutrino \(N_1\) is a dark matter candidate, and its mixing is so small that its effect on the active neutrino masses is negligible. This implies that one active neutrino mass is much lighter than the others (with mass smaller than \(\mathcal{O}(10^{-5})\) eV). Moreover, \(N_1\) also does not contribute significantly to the production of lepton asymmetries at any time. This process can, therefore, be described in an effective theory with only two sterile flavors \(N_{2,3}\).

While there is very little mixing between the active and sterile flavors at all temperatures of interest, the CP-violating oscillations between the sterile neutrinos can be essential for the generation of a lepton asymmetry. The transitions between them are suppressed by the active-sterile mixing matrix \(\theta = m_D M_M^{-1}\). The lepton asymmetries produced by \(N_{2,3}\) are crucial on two occasions in the history of the universe. On the one hand, the asymmetries generated at the early universe \((T \geq 140 \text{ MeV})\) are responsible for the generation of BAU via flavored leptogenesis. On the other hand, the later asymmetries \((T \sim 140 \text{ MeV})\) strongly affect the rate of thermal \(N_1\) production. Due to the latter, the requirement to produce the observed \(\Sigma_{DM}\) imposes indirect constraints on the particles \(N_{2,3}\).

### 2.3.3 Solution to Baryon Asymmetry and Dark Matter

The \(\nu_{\text{MSM}}\) consists of the same particles as the SM except for the sterile neutrinos which only couple to the active neutrinos. The thermal history of the universe during the radiation-dominant era is similar in both the models. The sterile neutrinos couple to the SM particles only via the Yukawa matrices \(F\), which are constrained by the seesaw relation. While the sterile neutrinos with masses below the electroweak scale cannot affect the entropy during the radiation-dominated era due to their small abundances, these can be the enough additional sources of CP-violation for the lepton chemical potentials in the plasma. The thermal history of the universe in the \(\nu_{\text{MSM}}\) is shown in Fig. 2.3.
2.3. HEAVY NEUTRAL LEPTON

Figure 2.3: Thermal history of the universe in the $\nu$MSM [20].
Baryogenesis

As mentioned above, because the sterile neutrinos $N_I$ are produced in a negligible amount during reheating due to their small Yukawa couplings $F$, the thermal history of the $\nu$MSM is similar to that of the SM for $T \gg T_{EW}$. The $\nu$MSM does not introduce any new mechanism in the radiation-dominanted era; the sterile neutrinos are produced thermally from the primordial plasma. During this non-equilibrium process, all the Sakharov conditions which are necessary for baryogenesis are fulfilled. The baryon number is violated by the SM sphalerons [21], and the oscillations among the sterile neutrinos can be the source of CP-violation by the complex phases in the Yukawa couplings $F_{ai}$. The abundance of $N_1$ remains negligible until $T \sim 100$ MeV due to its small Yukawa coupling, while $N_{2,3}$ are produced efficiently in the early universe. For $T > M$, flavored “lepton asymmetry” is generated [22] and $N_{2,3}$ reach equilibrium at the temperature $T_+$. Though the total lepton number

$$J_I^\mu = \bar{\nu}_{R,I} \gamma^\mu \nu_{R,I}$$

at $T_+ \gg M$ is very small, there are asymmetries between the two helicity states in the individual active and sterile flavors. Sphalerons, which only couple to the left chiral fields, can convert them into a baryon asymmetry. Because the washout of lepton asymmetries becomes efficient at $T \lesssim T_+$, it is necessary for baryogenesis that not all asymmetries are washed out at $T_{EW}$. This condition is fulfilled at $T_+ \geq T_{EW}$. The BAU at $T \sim T_{EW}$ can be estimated from today’s baryon-photon ratio $\eta_B$. Its precise value can be obtained by the data from the cosmic microwave background and large-scale structure [23],

$$\eta_B = (6.160 \pm 0.148) \cdot 10^{-10}. \quad (2.24)$$

The parameter $\eta_B$ is related to the remnant density of baryons $\Omega_B$, in the units of critical density, by $\Omega_B \simeq \eta_B/(2.739 \cdot 10^{-8} h^2)$, where $h$ parameterizes today’s Hubble rate $H_0 = 100 h$ (km/s)/Mpc. To generate this asymmetry, the effective masses $M_2(T)$ and $M_3(T)$ of the sterile neutrinos in the plasma should be quasi-degenerate at $T \geq T_{DM}$. Although the lepton asymmetries are washed out after $N_2$ and $N_3$ reach equilibrium, it is believed that some asymmetry is protected from this washout by the chiral anomaly. At $T = T_-$, $N_{2,3}$ are out of the equilibrium. During the resulting freezeout, the Sakharov conditions are again fulfilled, and new asymmetries are generated. In addition, a final contribution to the lepton asymmetries is generated when the unstable particles $N_{2,3}$ decay at the temperature $T_d$.

Dark Matter Production

The abundance of the lightest sterile neutrino $N_1$ remains below equilibrium at all times due to its small coupling. The amount of all dark matter in the universe cannot be explained in terms of the relic $N_1$ because a thermal production of these particles (Dodelson-Windrow mechanism [24]) is not sufficient without chemical potentials. However, in the presence of a lepton asymmetry in the primordial plasma, the dispersion relations of the active and sterile neutrinos are modified by the Mikheyev-Smirnov-Wolfenstein effect [25,26]. The thermal masses of the active neutrinos can be large enough to cause a level crossing between the dispersion relations for the active and sterile flavors at $T_{DM}$, resulting in a resonantly enhanced production of $N_1$. This mechanism requires the lepton asymmetry $|\mu_\alpha| \geq 8 \cdot 10^{-6}$ to be efficient enough to explain the entire observed dark matter density $\Omega_{DM}$ in terms of the $N_1$ relic neutrinos. Here, we have characterized the asymmetry as

$$\mu_\alpha = \frac{n_\alpha}{s}, \quad (2.25)$$
2.4 Experimental Status for Heavy Neutral Lepton Searches

The current limits and future prospects of the mixing between the muon neutrino and a single heavy neutrino in the mass range 100 MeV – 500 GeV are summarized in Fig. 2.4.

2.4.1 Current Limits from the DELPHI Experiment at LEP

The current best limit for the HNLs with sub-GeV masses was set by the DELPHI experiment at the Large Electron Positron collider (LEP) [28]. In the LEP-1, about $10^6$ $Z$ bosons were produced and HNLs from $Z$ boson decays were searched for.

2.4.2 Potential Heavy Neutral Lepton Search at ATLAS Experiment

HNLs with masses of sub-GeV or tens of GeV are produced via $Z$ bosons or $W$ bosons. In the Large Hadron Collider (LHC), protons collide at the center-of-mass energy of 13 TeV, and it produces approximately $10^9$ of $W$ bosons for 30 fb$^{-1}$ data. The HNLs have a relatively longer lifetime due to their weak coupling to the SM particles, and it makes a vertex displaced from the interaction point in the ATLAS detector. Typically, the lifetime of an HNL is given by [29]:

$$
\tau_N [s] = 4.49 \cdot 10^{-12}|U|^2(m_N [GeV])^{-5.19}.
$$  \hfill (2.26)
The tracks from the HNL’s vertices are not reconstructed since the ATLAS standard tracking assumes that the tracks originate from the interaction point. In this study, a dedicated method is applied to the tracks from displaced vertex (DV).
Chapter 3

LHC and the ATLAS Detector

3.1 Large Hadron Collider

Figure 3.1: The LHC and the associated accelerator systems at CERN [30].
The Large Hadron Collider (LHC) [31] is a 27-km-long circular proton accelerator located on the border of Switzerland and France at 100 m underground. The LHC accelerates protons and collides them at a center-of-mass energy of 13 TeV.

Various stages are necessary to accelerate the protons up to the desired energy, as shown in Fig. 3.1. To extract protons, hydrogen gas is injected into a metal cylinder, duoplasmatron, and the gas is then separated into its constituent protons and electrons by applying an electrical field to it. The protons are sent to a Radio Frequency Quadrupole (RFQ), where the beam is accelerated and focused by a quadrupole radiofrequency (RF) field. The protons are accelerated up to 750 keV and then injected into a linear accelerator called LINAC2. The linac tank is a multi-chamber resonant cavity tuned to a specific frequency which creates potential differences in the cavities that accelerate the protons up to 50 MeV. The following Proton Synchrotron Booster (PSB) with a circumference of 157 m accelerates the protons up to 1.4 GeV and accumulates them. Subsequently, a 628-m-long Proton Synchrotron (PS) accelerates the protons up to 25 GeV and compresses the protons in a bunch structure. The PS is responsible for providing 81 bunch packets with a 25 ns spacing for the LHC. The 7 km circumference Super Proton Synchrotron (SPS) raises the proton energy up to 450 GeV and the accelerated protons are injected into the LHC.

The protons are finally transferred to the LHC both in clockwise and anticlockwise directions. The LHC consists of eight 2.45-km-long arcs and eight 545-m-long straight sections. The arcs contain 154 dipole magnets each to maintain the orbit of the accelerated particles. Each arc contains 23 arc cells as shown in Fig. 3.2, and each arc cell has a 106.9-m-long structure consisting of the main dipole magnets, quadrupole magnets, and other multipoles magnets. The 1,232 superconducting dipoles made of NbTi are operated reliably at a nominal magnetic field of 8.33 T with superfluid helium at 1.9 K. The layout of a straight section depends on its specific use: beam collisions, injection, beam dumping, or beam cleaning. The main role of the RFQ cavities is to keep the proton bunches tightly bunched to ensure high luminosity at the collision points. Moreover, they deliver RF power to the beams during acceleration to the peak energy. The LHC uses eight cavities per beam, each delivering 2 MV corresponding to an accelerating field of 5 MV/m at 400 MHz. The cavities operate at 4.5 K. The LHC is designed to fill 39 bunch trains in total, and 2,808 bunches are included per beam. Each bunch contains approximately $10^{11}$ protons, and the beam bunches are collided at a crossing angle of 285 mrad.

![Figure 3.2: Schematic view of the LHC arc cells. These cells configure the unit of bending magnet.](image)

There are four detector sites on the LHC acceleration ring. ATLAS (A Toroidal LHC ApparatuS) [32] and CMS (the Compact Muon Solenoid) [33] are the detectors studying the various
3.1 LARGE HADRON COLLIDER

physics phenomena, whereas LHCb (study of physics in $B$-meson decays at LHC) \[34\] and ALICE (A Large Ion Collider Experiment) \[35\] are dedicated detectors to study $B$ physics and heavy ion collisions, respectively.

The LHC started its operation with a center-of-mass energy of 7 TeV in 2010 and of 8 TeV in 2011, and it provided an integrated luminosity of 4.7 fb$^{-1}$ and 20.3 fb$^{-1}$, respectively, by the end of its operation in 2012. Then the LHC was upgraded, and it restarted operation with a largely increased center-of-mass energy of $\sqrt{s} = 13$ TeV, where $\sqrt{s}$ is the total center-of-mass energy of the colliding protons. During operation in 2016, the peak luminosity was $(0.7 - 1.4) \times 10^{34}$ cm$^2$s$^{-1}$. Due to the high frequency of collisions and high density of bunches, a number of proton collisions called “pileup” occur at the bunch crossings. The average number of interactions for a bunch crossing is defined as the average pileup $\mu$, and it increases as the peak luminosity increases. The typical machine parameters for each year are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
<td>4</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>$1/f_{\text{rev}}$: bunch spacing [ns]</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\beta^*$ at the interaction point [cm]</td>
<td>60</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>$\theta_c$: crossing angle [\mu rad]</td>
<td>145</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>$\epsilon$: normalized emittance at the start filling [\mu m]</td>
<td>2.2</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td>$n$: maximum bunch population [$10^{11}$ protons/bunch]</td>
<td>1.6</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>Maximum number of bunches per injected train</td>
<td>144</td>
<td>144</td>
<td>96</td>
</tr>
<tr>
<td>$N_b$: maximum number of bunches</td>
<td>1374</td>
<td>2244</td>
<td>2220</td>
</tr>
<tr>
<td>$\mathcal{L}(t)$: instantaneous luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>&gt; 0.7</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Number of interactions per crossing</td>
<td>20.7</td>
<td>13.4</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Table 3.1: Machine parameters of the LHC \[36\].

The beam intensity of the LHC is expressed as the instantaneous luminosity $\mathcal{L}(t)$. If a physics process with its cross section ($\sigma$) occurs at the luminosity of $\mathcal{L}$, the rate of the interactions is $\sigma \times \mathcal{L}(t)$. The instantaneous luminosity, $\mathcal{L}(t)$, can then be mentioned as the frequency of the particles recognizing each other at a unit of time and space. If we assume that the two beams are identical and distributed as Gaussian, the instantaneous luminosity is expressed as

$$\mathcal{L}(t) = N_b \times F \frac{n^2 f_{\text{rev}} \gamma}{4\pi \epsilon \beta^*},$$

(3.1)

where $N_b$ is the number of bunches, $n$ is the number of protons included in one bunch, $\gamma$ is the Lorentz factor, $\beta^*$ is the beta-function at the interaction point, and $\epsilon$ is the normalized beam emittance. $F$ is the geometric luminosity reduction factor considering the beam crossing angle at the interaction point and is defined as

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \sigma_{xy}}\right)^2},$$

(3.2)

where $\theta_c$ is the full crossing angle of the two beams at the interaction point, $\sigma_z$ is the length of a bunch, and $\sigma_{xy}$ is the transverse beam size. The peak luminosity in the 2016 runs (which are used in this study) and the mean number of interactions per bunch crossing in 2015 – 16 are shown in Fig. 3.3.
CHAPTER 3. LHC AND THE ATLAS DETECTOR

Figure 3.3: Peak luminosity in 2016 (left) [37]; and mean number of interactions per bunch crossing in 2015 – 16 (right) [38].

3.2 ATLAS Detector

Figure 3.4: Cut-away view of the ATLAS detector.

A Troidal LHC ApparatuS (ATLAS) [39] is a general-purpose detector installed in one of the collision points of the LHC. It is designed to measure a wide variety of physics processes and consists of three parts with various sets of detectors depending on the purpose (Fig. 3.4). The innermost part of the ATLAS detector, close to the interaction point, has an inner detector which measures the particle momenta in the solenoid magnetic field. It consists of layers of silicon sensors and gas chambers. The middle part of the ATLAS detector consists of calorimeters which measure the particle energies. The electromagnetic (EM) calorimeter measures the electrons and photons
energies via the electromagnetic interaction, and the hadronic (HAD) calorimeter measures the hadron energies via the electromagnetic and strong interactions. The outermost part contains the muon spectrometer which measures the momenta of particles penetrating the calorimeters. The physics objects generated from \(pp\) collisions, such as electrons, muons, photons, and hadrons, are identified with the ATLAS detector as shown in Fig. 3.5. The ATLAS detector is approximately 44 m wide and 25 m high, and its weight is approximately 7,000 tons. It almost covers the full solid angle around the interaction point by a cylindrical barrel and two end-caps.

![Figure 3.5: Illustration of the detection of stable particles in the ATLAS detector [40].](image)

### 3.2.1 Coordinate System

To identify the detector positions and particle orientations, the right-handed Cartesian coordinate system is used. The origin is set at the interaction point, the \(x\)-axis points to the center of the LHC ring, and the directions of the \(y\)-axis and \(z\)-axis are set as the directions of up and the beam axis, respectively, as shown in Fig. 3.6. The cylindrical coordinate system is expressed as \((r, \phi, z)\), where \(r\) is the radial distance and \(\phi\) is the azimuthal angle. \(\phi\) is defined such that it runs from \(-\pi\) to \(\pi\) with respect to the \(x\)-axis, and the plane defines defined by the \(x\)- and \(y\)-axes is called a “transverse” plane. The polar angle \(\theta\) is defined in the expression for the modified cylindrical coordinate system \((\theta, \phi, z)\). Here, \(\theta\) runs from 0 to \(\pi\) with respect to the \(z\)-axis. The two end-caps called “A-side” and “C-side” correspond to positive and negative positions in the \(z\)-axis, respectively. The pseudo-rapidity \(\eta\) is defined as:

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

(3.3)
Using $\eta$ is advantageous over directly using $\theta$. The difference in the pseudo-rapidity $\eta$ between particles, $\Delta \eta$, is invariant under the boost in the $z$-direction.

![ATLAS coordinate system](image)

Figure 3.6: ATLAS coordinate system.

Usually, the particles generated in the LHC are boosted in the $z$-direction. This is due to the asymmetry of the interacting partons in a proton. From this point of view, it is convenient to define Lorentz invariant variables for particle momentum $p$ and energy $E$ called transverse momentum and transverse energy, respectively, as follows:

$$p_T = p \sin \theta, \quad E_T = E \sin \theta.$$  \hspace{1cm} (3.4)

The advantages of these variables are that they provide the momentum and energy in the center-of-mass system of the interaction, and the vector sum of all particles are conserved before and after a collision.

The difference in the angle between two particles is expressed with $R$ which is defined as:

$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}.$$  \hspace{1cm} (3.5)

### 3.2.2 Magnets

The magnet system consists of four large superconducting magnet sub-systems, a central solenoid (CS), and three open-air toroidal magnets. These are cooled to 4.5 K by liquid helium and provide the magnetic fields shown in Fig. 3.7 to bend the trajectory of the charged particles to measure their momenta.

The CS has a 2.5 m diameter and is installed inside the EM calorimeter, providing a uniform 2 T axial magnetic field to the inner detector. The strength of the magnetic field slightly weakens along the beam axis due to the finite length of the CS. The radiation length of the CS is $\sim 0.66X_0$. 


The toroidal system provides the magnetic field in the $\phi$ direction and bends muons in the $\theta$ direction to measure their momenta. The barrel toroid consists of 8 flat superconducting race-track coils. Each coil has a 25.3 m axial length and extends from 4.7 m to 10.05 m in the radial direction. The end-cap toroids have a 5 m length, 10.7 m outer diameter, and 1.65 m inner diameter. The maximum value of the toroidal magnetic field is 3.9 T in the barrel region and 4.1 T in the end-caps regions.

Figure 3.7: Illustration of the ATLAS magnet [41]. Inner cylinder shows the magnet field produced by the solenoid and the outer red rings show the toroids.

### 3.2.3 Inner Detector

The inner detector consists of a silicon pixel detector (PIXEL), a semiconductor tracker (SCT), and a transition radiation tracker (TRT) and covers the region $|\eta| < 2.5$. All sub-detectors are composed of concentric cylinders in barrels and of disks or wheels which are orthogonal to the beam axis at the end-caps as shown in Fig. 3.8. The total length of the inner detector is 7 m, the outer diameter is 1.5 m, and all the regions are in the range of the 2 T magnetic fields generated by the CS. The PIXEL and the SCT are the silicon detectors which accomplish the fast response and high granularity of position identification and TRT is the gas detector which covers a large region.

The inner detector measures the tracks of charged particles by identifying the positions where the particles traverse each detection layer. The tracks are reconstructed by combining these hits. The electric charge of a particle is identified from the direction in which the particle bends. The transverse momentum ($p_T$ [GeV]) is calculated using the Sagitta ($S$ [m]) and the Chord ($L$ [m]) in the transverse plane as shown in Fig. 3.9.

$$p_T \sim \frac{0.3BL^2}{8S},$$

(3.6)
Figure 3.8: Schematic view of the inner detectors [42].
where $B$ [T] is the strength of the magnetic field. The momentum resolution of the tracks neglecting the effect of multiple scattering is calculated as

$$
\frac{\sigma(p_T)}{p_T} = \frac{40\sigma(x)p_T}{BL^2} \sqrt{\frac{5}{N+4}} \quad \text{for } N \geq 10,
$$

where $\sigma(x)$ is the intrinsic position resolution for each detection layer and $N$ is the number of hits associated with the track. The momentum resolution of a particle with high $p_T$ worsens as it has a small Sagitta. In low $p_T$ regions, the resolution further worsens due to multiple scattering.

![Illustration of momentum measurement using Sagitta (S) and Chord (L).](image)

Figure 3.9: Illustration of momentum measurement using Sagitta (S) and Chord (L).

The total thickness of the inner detector equals to $0.4X_0$ at $\eta = 0$, and it increases in the forward region up to $1.5X_0$ due to the cables and supporting materials called services. The general parameters of the inner detector, such as resolutions and radial extensions, are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Radial extension, $R$ [mm]</th>
<th>Length, $z$ [mm]</th>
<th>Number of layers</th>
<th>Intrinsic resolution [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>$25 &lt; R &lt; 30$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IBL</td>
<td>$R = 33.25$</td>
<td>$0 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>PIXEL barrel</td>
<td>$50.5 &lt; R &lt; 122.5$</td>
<td>$0 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>PIXEL end-cap</td>
<td>$88.8 &lt; R &lt; 149.6$</td>
<td>$495 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>SCT barrel</td>
<td>$299 &lt; R &lt; 514$</td>
<td>$0 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>SCT end-cap</td>
<td>$275 &lt; R &lt; 560$</td>
<td>$839 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>TRT barrel</td>
<td>$563 &lt; R &lt; 1082$</td>
<td>$0 &lt;</td>
<td>z</td>
</tr>
<tr>
<td>TRT end-cap</td>
<td>$644 &lt; R &lt; 1004$</td>
<td>$848 &lt;</td>
<td>z</td>
</tr>
</tbody>
</table>

Table 3.2: Typical resolutions and detector parameters for the inner detector sub-systems [43, 44].

**PIXEL**

The PIXEL is located at the innermost part of the inner detectors and it requires the highest position resolution. The PIXEL consists of the “insertable b-layer” (IBL) and three pixel layers in
the barrel region and three pixel disks in each end-cap. In the barrel region, the layers are located between 31 mm and 122.5 mm of radial distance; the innermost layer is IBL and the second layer is called B-Layer. The total ionization dose (TID) is 2.5 MGy and the non-ionizing energy loss (NIEL) is \(5 \times 10^{15}\) 1MeV neq/cm\(^2\). The planar and 3D sensors are used 75% in the central region and 25% in the highest \(\eta\) region. The planar sensor is also used in the outer layers, and it is an n-type Si bulk wafer with surface electrodes using n\(^+\)-implants as shown in Fig. 3.11. The thickness of the sensor is 250 \(\mu\)m. The 3D sensor is a p-type Si bulk wafer with pillar electrodes penetrating the bulk using n\(^+\)- and p\(^+\)-implants. The 3D sensors has a lower depletion voltage and faster charge collection; however, due to its higher capacitance, it has a larger noise and high cost. The thickness of the 3D sensor is 230 \(\mu\)m. The pixel pitch of the IBL is 50 \(\times\) 250 \(\mu\)m\(^2\) and that of the other pixels is 50 \(\times\) 400 \(\mu\)m\(^2\). The pixel matrix of each module is 80 \(\times\) 328 for the IBL and 144 \(\times\) 328 for the other pixels. In total, there are 2,500 modules and 92 million channels. The PIXEL is operated at a low temperature to achieve good performance and decrease the radiation damage.

![Image of the PIXEL detector](image)

**Figure 3.10:** The PIXEL detector (left) and a pixel module (right) [45].

**SCT**

The SemiConductor Tracker (SCT) consists of a four-layer double-sided micro-strip silicon detector in the barrel region and nine disks for each end-cap operated in C\(_3\)F\(_8\) cooling (\(-7\) to \(+4.5\) °C on the sensor). The design of the modules is different for the barrel and end-caps as shown in Fig. 3.12. The SCT modules are made of two p-on-n 63.6 \(\times\) 64 mm\(^2\) single-sided sensors, and the overall length is 128 mm. A sensor has 768 strips with a 12 cm length and a 80 \(\mu\)m pitch and is read out by six application specific integrated circuits (ASICs). An SCT module consists of two sensors glued at a 40 mrad stereo angle to obtain two-dimensional information. The SCT has 4088 modules and 6.3 million channels.
3.2. ATLAS DETECTOR

Figure 3.11: Schematic view of a PIXEL planar sensor (left) [46] and a 3D sensor (right) [47].

Figure 3.12: Schematic view of the SCT modules for the barrel (left) and end-caps (right) [39].

SCT Efficiency

The LHC Run2 started from June 2015 with a bunch spacing of 50 ns. The SCT achieved 99.5\% or better hits-on-track efficiency at that time. In August 2015, the bunch spacing became 25 ns. At that time, a drop in the SCT hits-on-track efficiency was observed due to the high hit occupancy. The detail of lower efficiency depends on the SCT readout mode. The SCT reads out the hits information, which belongs to the previous, current, and next bunch crossings. To use this information, the SCT has two data acquiring modes: an X1X mode and a 01X mode. The requirement of each mode is as follows.

- **01X mode**: hits in the current bunch crossing are necessary but no hits in the previous bunch crossing are necessary.
- **X1X mode**: hits in the current bunch crossing are necessary.

In the 50 ns bunch space crossing, the data were collected with the X1X mode. On the other hand, in the 25 ns bunch space crossing, we first obtained data in the X1X mode and then changed to the 01X mode. In both cases, the efficiency of SCT was lower than that in the 50 ns bunch space crossing. The efficiency drop was larger in the inner layer for the 01X mode and there was no significant layer dependence for the X1X mode (Figs. 3.13 and 3.14). The total drop was approximately 0.5\%. 
Figure 3.13: Comparison of the SCT efficiencies for the runs with 50 ns bunch space crossing in the X1X mode and 25 ns bunch space crossing in the 01X mode.
Figure 3.14: Comparison of the SCT efficiencies for the runs with 50 ns bunch space crossing in the X1X mode and 25 ns bunch space crossing in the X1X mode.
In the case of the 01X mode, it is easy to understand the efficiency drop. In this mode, the SCT strips that have hits in the previous bunch crossing become dead strips in the current bunch crossing as shown in Fig. 3.15. The efficiency drop means that we lose some portion of the data in the 01X mode.

In the X1X mode, the reason for the efficiency drop is more complicated. The tracks which make large charge deposits can leave hits in the next bunch crossing. Such a track in the previous bunch crossing has 11X timing hits in the current bunch crossing as shown in Fig. 3.15 and also has 10X timing hits. If the track in the previous bunch crossing has enough 11X timing hits, it is also reconstructed in the current bunch crossing with more holes than those in the original track due to the 10X timing hits. Therefore, the X1X mode in the 25 ns bunch space collision runs has lower SCT efficiencies.

![Figure 3.15: Scheme of low efficiencies in the 01X mode (left) and the X1X mode (right).](image)

In both cases, the previous bunch crossing affects the SCT efficiencies. To observe this effect, the efficiencies in the events of the first bunch crossings in the bunch trains are calculated. In the first bunch event, there are no previous bunch crossing effects. In such events, the efficiencies are 0.4% higher than the usual events (Fig. 3.16).

As mentioned above, each SCT hit has three bunch crossing information. Using this information, the tracks in the current bunch crossing and in the previous bunch crossing can be separated as shown in Fig. 3.17 (left). The cluster of tracks with no 11X strips in the figure are constructed by tracks in the current bunch crossing and the peak on the left are constructed by the previous bunch crossing. Because the hits of PIXEL do not have three bunch crossing information, we can ensure that the tracks are constructed in the current bunch crossing by necessitating more than three PIXEL hits in the tracks. If PIXEL hits are required, the peaks on the left are disappear (Fig. 3.17).

To remove the tracks from the previous bunch crossing using these information, two additional options are implemented in SCT clustering.

- Majority 01X: the number of 01X hits should be more than that of 11X for each SCT cluster.
Figure 3.16: Comparison of the SCT efficiencies for all events (red) and the events of first bunch crossing in the bunch trains (black).

Figure 3.17: The number of 01X hits and the number of X1X hits for all tracks (left) and for tracks which have more than three PIXEL hits (right).
• InnerMost X1X: X1X requirement is applied to the innermost layer of the SCT and 01X is required for the others.

In both cases, the tracks from the previous bunch crossing disappear (Fig. 3.18).

![Figure 3.18: The number of 01X hits and the number of X1X hits for tracks when the majority 01X option is required (left) and the InnerMost X1X option is required (right).](image1)

The efficiencies obtained for the two modes are compared in Fig. 3.19. The efficiencies reduce when the majority 01X is applied. This is because fake tracks are reconstructed due to the clusters which have 11X strips. The efficiencies are recovered when X1X is required for the innermost layer and 01X is required for the other layers. In this option, the strips which have hits in the previous bunch crossing are not treated as dead strips, and few tracks from the previous bunch crossing are reconstructed.

![Figure 3.19: SCT efficiencies when the two new options are applied.](image2)

The efficiency of SCT reduces in the 25 ns bunch space crossing collision runs due to high occupancy. SCT has two read-out modes; in both the modes, a decrease in efficiency is observed
because of different reasons. Two additional options in SCT Clustering are prepared to improve the SCT efficiency. When X1X is required in the innermost layer and 01X is required for other layers, the efficiency increases.

**TRT**

The transition radiation tracker (TRT) is in the outermost part of the inner detector which consists of 370,000 cylindrical drift tubes. The TRT measures particle momentum and distinguishes electrons from other particles using the transition radiation. The barrel region which consists of 73 layers has 52,544 straw tubes of 4 mm diameter made of a carbon fiber film of 60 μm thickness; a Kapton reinforcement acts as the cathode. In the center of a tube, a 30 μm diameter of gold-plated tungsten wire is placed as the anode. In the straw, mixture gas is filled. It consists of 70% of Xe for good X-ray absorption, and 27% of CO₂ to increase the electron drift velocity and photon-quenching, and 3% of O₂ to enhance the operation stability. A 1.5 kV voltage is applied to the cathode and the maximum drift time is 45 ns. The signal is read out from both the ends of the straw to identify the positions of the passing particles. There are 160 layers and 122,880 straw tubes in the end-cap region. Polymer fibers in the barrel and foils in the end-caps are placed among the straws to obtain transition radiation. When particles penetrate the border of the materials, dipoles resulting in radiation photons are induced, and their strength is proportional to the Lorentz boost factor \( \gamma = E/m \). The emitted X-rays are absorbed by the Xe gas in TRT, and they constitute additional collected energy. This transition radiation is used for electron identification. For this purpose, the front-end system adopts two thresholds. The lower threshold is set to 300 eV for minimum ionizing particle (MIP), and the higher threshold is set to 6 or 7 keV for electron identification.

![Figure 3.20: Structure of TRT](image-url)
3.2.4 Calorimeter System

The ATLAS calorimeter surrounds the inner detector and covers the pseudo-rapidity $|\eta| < 4.9$. It consists of an electromagnetic calorimeter (EM calorimeter), hadronic calorimeter (HAD calorimeter), and forward calorimeter which stop various particles in the detector and measures their energy. The fast electronic system based on fast processing of particle identification and energy measurement is employed for the first level trigger (L1). The sampling calorimeter is adopted as the ATLAS calorimeter and it is composed of alternately arranged absorber plates to induce particle shower and active layers to measure energy. The combination of the absorber and active layer, and their granularity is dependent on the $\eta$ region and classified roughly into two types. The first one is the Liquid-Argon (LAr) sampling calorimeter in which the absorber layer made of lead or copper and the active layer made of liquid argon are arranged alternatively. The other one is the tile calorimeter where a scintillator is adopted for the active layers and steel for the absorber layers. The details of the composed active material and absorber, $\Delta\eta \times \Delta\phi$ segments, and $\eta$ coverage are summarized in Table 3.3.

Figure 3.21: Schematic of the calorimeter [48].

The particles traveling in the calorimeter deposit their energy by interacting electromagnetically and/or hadronically. The charged particle generated by such interactions ionizes the active material in the calorimeter. The particle energy is calculated by measuring the ionization or the number of particles in a shower which is proportional to the energy of the incident particle. The shower
### 3.2. ATLAS DETECTOR

#### Table 3.3: $\Delta \eta \times \Delta \phi$ segments and $\eta$ coverage of the calorimeter sub-systems.

<table>
<thead>
<tr>
<th>Coverage</th>
<th>$\Delta \eta \times \Delta \phi$</th>
<th>Absorber</th>
<th>Active material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic calorimeter (LAr barrel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-sampler</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.52$</td>
</tr>
<tr>
<td>Layer-1</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.4$</td>
</tr>
<tr>
<td>Layer-2</td>
<td>$1.4 &lt;</td>
<td>\eta</td>
<td>&lt; 1.475$</td>
</tr>
<tr>
<td>Layer-3</td>
<td>$1.4 &lt;</td>
<td>\eta</td>
<td>&lt; 1.475$</td>
</tr>
<tr>
<td>Electromagnetic calorimeter (LAr end-cap)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-sampler</td>
<td>$1.5 &lt;</td>
<td>\eta</td>
<td>&lt; 1.8$</td>
</tr>
<tr>
<td>Layer-1</td>
<td>$1.375 &lt;</td>
<td>\eta</td>
<td>&lt; 1.425$</td>
</tr>
<tr>
<td></td>
<td>$1.425 &lt;</td>
<td>\eta</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td></td>
<td>$1.5 &lt;</td>
<td>\eta</td>
<td>&lt; 1.8$</td>
</tr>
<tr>
<td></td>
<td>$1.8 &lt;</td>
<td>\eta</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td></td>
<td>$2.0 &lt;</td>
<td>\eta</td>
<td>&lt; 2.4$</td>
</tr>
<tr>
<td></td>
<td>$2.4 &lt;</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td></td>
<td>$2.5 &lt;</td>
<td>\eta</td>
<td>&lt; 3.2$</td>
</tr>
<tr>
<td>Layer-2</td>
<td>$1.375 &lt;</td>
<td>\eta</td>
<td>&lt; 1.425$</td>
</tr>
<tr>
<td>Layer-3</td>
<td>$1.425 &lt;</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td></td>
<td>$2.5 &lt;</td>
<td>\eta</td>
<td>&lt; 3.2$</td>
</tr>
<tr>
<td>Layer-3</td>
<td>$1.5 &lt;</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>Hadronic calorimeter (Tile barrel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer-1 and 2</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.0$</td>
</tr>
<tr>
<td>Layer-3</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.0$</td>
</tr>
<tr>
<td>Hadronic calorimeter (Tile extended-barrel)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer-1 and 2</td>
<td>$0.8 &lt;</td>
<td>\eta</td>
<td>&lt; 1.7$</td>
</tr>
<tr>
<td>Layer-3</td>
<td>$0.8 &lt;</td>
<td>\eta</td>
<td>&lt; 1.7$</td>
</tr>
<tr>
<td>Hadronic calorimeter (LAr end-cap)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner</td>
<td>$1.5 &lt;</td>
<td>\eta</td>
<td>&lt; 3.2$</td>
</tr>
<tr>
<td>Outer</td>
<td>$1.5 &lt;</td>
<td>\eta</td>
<td>&lt; 3.2$</td>
</tr>
<tr>
<td>Forward calorimeter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner</td>
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<td>\eta</td>
<td>&lt; 4.83$</td>
</tr>
<tr>
<td>Middle</td>
<td>$3.24 &lt;</td>
<td>\eta</td>
<td>&lt; 4.81$</td>
</tr>
<tr>
<td>Outer</td>
<td>$3.32 &lt;</td>
<td>\eta</td>
<td>&lt; 4.75$</td>
</tr>
</tbody>
</table>
formed by electromagnetic interaction is called EM shower and that by hadronic interaction is called hadronic shower. The energy resolution of the calorimeter is defined as

$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E/[\text{GeV}]}} + \frac{B}{E/[\text{GeV}]} + C,$$

(3.8)

where the constants $A$ depends on the absorber, active material, and sampling fraction of the calorimeter. The term $A/\sqrt{E}$ is called the “stochastic” term and expresses the interaction fluctuations. The contributions from electronics and pile-up noise are considered in the second term. The constant $C$ includes reaction the non-uniformity, calibration, dead material, and the energy loss before the calorimeter.

The incident electrons and photons mainly cause bremsstrahlung and pair creation, respectively, and generate EM shower in the calorimeter. The electrons and positrons continue to interact until the energy is below the critical energy ($E_c$), where the energy loss by bremsstrahlung equals that by ionization and excitation. The length at which the energy of the electrons and positrons goes below the critical energy is referred to as the radiation length $X_0$ [g/cm$^2$] and defined by the energy loss due to bremsstrahlung:

$$- \frac{dE}{dx} = \frac{E}{X_0} \text{ for } X_0[g/cm^2] = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln[183/Z^{1/3}]}.$$

(3.9)

- $A$ : mass number of material
- $Z$ : atomic number of material
- $N_A$ : Avogadro constant
- $r_e$ : classical electron radius
- $\alpha$ : fine structure constant

The radiation length and Moliere radius $R_M$ [g/cm$^2$] are parameters expressing characteristic length and lateral size of the EM shower. The longitudinal length of the shower shape including 95% of its energy is described using $t_{max}$, which is defined as the longitudinal position where the shower deposits maximum energy:

$$L_{95%}[X_0] = t_{max} + 0.08Z + 9.6,$$

(3.10)

where $t_{max} = \ln(E/E_c) - 1$ for the shower induced by electrons and $t_{max} = \ln(E/E_c) - 0.5$ for that induced by photons. The Moliere radius is defined as the radius of the cylinder which contains 90% of the shower energy and is approximated by

$$R_M[g/cm^2] = \frac{21}{E_c [\text{MeV}]} X_0.$$

(3.11)

The critical energy at which $dE/dx$ of ionization equals that of bremsstrahlung depends on the absorber material. The hadronic shower induced by the strong interactions has a more complex structure. The interaction length ($\lambda$) is described as follows:

$$\lambda[g/cm^2] = \frac{A}{N_A \sigma_{\text{inel, pA}}} \sim \frac{A^{1/3}}{N_A \sigma_{\text{inel, pp}}},$$

(3.12)

where $\sigma_{\text{inel, pA}}$ is the cross section of the inelastic collisions between protons and nucleons approximated as $\sigma_{\text{inel, pp}} A^{2/3}$ using that of protons and protons ($\sigma_{\text{inel, pp}}$). As an approximation, the ratio of the interaction length and the radiation length is considered as $A^{4/3}$. 
3.2. ATLAS DETECTOR

Electromagnetic Calorimeter

The basic unit of the LAr calorimeter consists of the gaps filled with liquid argon generating ionized electrons, the copper-Kapton electrode collecting ionized charge, and the steel-cladded lead absorber developing EM shower which are arranged in an accordion geometry. A bias voltage of 2000 V is applied between the electrodes and the absorber resulting in a 450 ns drift time. The readout signal is amplified by the pre-amplifier and shaped to a pulse width of 13 ns by a bi-polar shaper. The detector is kept at a temperature of 88 K by the cryostats surrounding the barrel EM calorimeter. The geometry and cell segmentation change between the barrel and end-caps depending on the desired function.

The barrel EM calorimeter consists of three sampling blocks with different $\eta \times \phi$ segmentations along the shower. The first sampling layer, referred to as a “strip layer”, has the finest $\eta \times \phi$ granularity ($0.0031 \times 0.098$) and identifies the precise angular position of an incident particle. In the second sampling layer, almost all energies of the shower are measured, and it has the largest sensitive region corresponding to $16X_0$. The third layer measures the tail of the EM shower and provides a longitudinal profile together with information of the other layers. For compensating the energy loss in the upstream, a pre-sampling layer is placed in front of the first layer for the barrel and both the end-caps. The total thickness is $> 22X_0$ in the barrel and $> 24X_0$ in the end-caps which can measure the EM shower produced by the photons and electrons with sub-TeV energy. The region between the barrel and end-caps is used for services and not fully instrumented.

The resolution is given by

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E[GeV]}} \oplus \frac{17\%}{E[GeV]} \oplus 0.7\%.$$  \(3.13\)

The resolution of the reconstructed objects can be improved by the calibration using the details of the shower profile and information from other sub-detectors. The EM calorimeter consists of LAr active layers with Kapton electrodes and lead absorber layers and has complete $\phi$ symmetry. The EM calorimeter is separated into a barrel region ($|\eta| < 1.475$) and two end-cap regions ($1.375 < |\eta| < 3.2$). The barrel calorimeter is composed of two identical cylinders separated into positive and negative $\eta$ regions, and there is a 6 mm gap at $z = 0$. Each end-cap calorimeter is divided in two coaxial wheels. The outer wheel covers $1.375 < |\eta| < 2.5$ and inner wheel covers $2.5 < |\eta| < 3.2$. The wave of accordion electrode structure in the barrel (end-caps) region becomes larger along the $\eta$ ($z$) direction, and the gap of LAr is constant. The calorimeter has three longitudinal segments for precision measurement. The total number of readout channels is 190,000.

Hadronic Calorimeter

The HAD calorimeter consists of the tile calorimeter and the LAr calorimeter depending on the $|\eta|$ region. The tile calorimeter is composed of steel absorber plates and polystyrene scintillator tiles and is divided into the barrel ($|\eta| < 1.0$) and extended-barrel ($0.8 < |\eta| < 1.7$) regions. Each tile calorimeter region is divided longitudinally into three sampling layers and each section has an interaction length of $1.5\lambda, 4.1\lambda, 1.8\lambda$ for the barrel and $1.5\lambda, 2.6\lambda, 3.3\lambda$ for the extended-barrel. The number of readout channels is approximately 10,000. The generated scintillation light is read out by photomultiplier tubes through wave length-shifting fibers.

The LAr hadronic end-cap calorimeter consists of a copper plate absorber and a LAr active material. It has an inner wheel and an outer wheel divided into two longitudinal sections composed
of 32 wedge-shaped modules. The module of the inner (outer) wheel consists of 24 copper plates with 25 (50) mm thickness and a 12.5 mm (25 mm) thick front plate with an 8.5 mm active LAr layer. To maintain the rigidity of the modules, seven stainless steel tie-rods are penetrated. The number of total readout channels is 5,632.

The detector resolution is given by

\[ \frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E \, \text{[GeV]}}} \oplus 3\% \text{ for tile HAD calorimeter,} \quad (3.14) \]
\[ \frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E \, \text{[GeV]}}} \oplus 10\% \text{ for end-cap LAr HAD calorimeter.} \quad (3.15) \]
Forward Calorimeter

The LAr calorimeter is located in the very forward region next to the beam line covering $3.1 < |\eta| < 4.9$ and integrates all jets or particles from the hard scatterings of extremely boosted particles. The forward calorimeter consists of three sampling layers with 45 cm modules. The first layer has a copper absorber, while the remaining layers have tungsten layers. The interaction length is $10\lambda$.

3.2.5 Muon Spectrometer

The muon spectrometer is a set of detectors to detect the particles penetrating the calorimeter. It identifies muons and measures their momenta. For this purpose, the muon spectrometer consists of multiple layers, and each layer measures the positions of the traversing muons. Similar to the inner detector, the tracks are reconstructed with the positions of hits in the muon spectrometer, and muon momenta are calculated from the Sagitta of the trajectories. The muon spectrometer is used as the trigger to obtain the data which contain muon candidates with high $p_T$. The muon spectrometer consists of four gaseous sub-detectors surrounding the large region outside of the calorimeter, namely, the Monitored Drift Tubes (MDT), the Cathode Strip Chambers (CSC), the Resistive Plate Chambers (RPC), and Thin Gap Chambers (TGC). The MDT and CSC are the wire detectors for the precise measurement of muon momenta in $|\eta| < 2.7$. The RPC and TGC which are fast-response detectors are introduced for trigger in $|\eta| < 2.4$. These provide a faster response than the LHC bunch spacing ($= 25$ ns) as the precision tracking system measures the muon trajectory in time of $O(\mu s)$. The precision chamber has a transverse momentum resolution of 10% for muons with 1 TeV corresponding to the 50 $\mu$m position resolution for 500 $\mu$m Sagitta.

Monitor Drift Tubes (MDT)

The MDT is a gas drift chamber consisting of the basic detection elements of aluminum tubes with a 30 mm diameter covered by a 400 $\mu$m thick of wall. The drifting electrons are absorbed in the tungsten-Rhenium wire with a 50 $\mu$m diameter in the center of the tube by applying a 3080 V bias voltage. The mixture gas of Ar (93%) and CO$_2$ (7%) maintains the maximum drift time of 700 ns. The position resolution of a single wire is 80 $\mu$m. There are three MDT chambers in the barrel and two end-caps. The MDT covers the region $|\eta| < 2.0$. The $\eta$ coverage is restricted by the maximum durable rate (150 cm$^{-1}$s$^{-1}$). The CSC covers the further forward region. To achieve the desired precision position resolution, the innermost layer consists of four tube-layers and the other outer layers each consist of three tube layers. Each cylindrical MDT station has 40 $\mu$m resolution and the combined resolution is 30 $\mu$m.

Cathode Strip Chamber (CSC)

The CSC is a multi-wire proportional chamber (MWPC) providing two-dimentional position information which covers the forward region of the end-caps ($2.0 < |\eta| < 2.7$) with a gas mixture of Ar (80%), CO$_2$ (20%). It is operated by applying a 1900 V bias voltage. The cells are symmetric from the point of view of pitch of the readout cathode and anode-cathode spacing (2.54 mm). Because the spacing resolution of CSC is sensitive to the track’s inclination and Lorentz angle, these are tilted where the tracks from the interaction point are orthogonally incident on the surface of the chamber. The CSC is the multi-wire proportional chamber (MWPC) and has W-Re anode wires.
with 30 $\mu$m diameter and 2.5 mm pitch. The signal is readout by the two cathode-strip layers made of polyurethane foam laminated to a copper-clad.

Resistive Plate Chamber (RPC)

The RPC is a digital gas detector dedicated to the fast time response for the trigger. It is mechanically mounted on the surface of the barrel MDT and covers pseudo-rapidity $|\eta| < 1.05$. The elementary detection unit is a gas gap filled with non-flammable gas mixture (94% $\text{C}_2\text{H}_2\text{F}_4$, 5% Iso-$\text{C}_4\text{H}_8$, 0.3% $\text{SF}_6$). A uniform high electric field ($\sim 4900$ V/mm) is applied to amplify the ionized electrons causing an avalanche. The signal is read out by the metal strips attached to both ends of the gaps with the interval of 30 mm–39.5 mm.

Thin-Gap Chamber (TGC)

The TGC is a multi-wire proportional chamber characterized by a notably small distance (1.4 mm) between the anode wires and readout cathode strips. The quick drain of secondary electrons is achieved by the quenching gas with a mixture of $\text{CO}_2$ (55%) and n-pentane (45%) and 5 ns timing.
response is obtained. The TGC also contributes to momentum measurement. Three modules are placed for each end-cap; the innermost module covers $1.05 < |\eta| < 2.7$ and the remaining two modules cover $1.05 < |\eta| < 2.4$. The trigger is generated for the tracks in the range $1.05 < |\eta| < 2.4$, measuring all track momenta.

### 3.2.6 Trigger System and Data Acquisition System

The ATLAS detector cannot record all collision events produced at the LHC. Almost all these events are trivial QCD events containing low $p_T$ jets, and the data rate reaches 100 PB/s. Trigger is a system that uses a simple criteria to decide which events in a particle detector are to be retained when only a small fraction of the total can be recorded. The ATLAS trigger and data acquisition (TDAQ) system chooses events with interesting physics properties and records them.
CHAPTER 3. LHC AND THE ATLAS DETECTOR

A schematic view of the ATLAS TDAQ system is shown in Fig. 3.24. The trigger system consists of a hardware level 1 (L1) trigger and a software-based high-level trigger (HLT). The basic idea is that the trivial QCD events are removed in L1 by fast particle reconstruction, and the filtering is performed in the HLT with further sophisticated reconstruction and energy measurements. The event rate is reduced from 40 MHz of the bunch crossing rate to 100 kHz at L1 and 1 kHz on an average at HLT.

At L1, the fast custom-made electronics obtains a Region of Interest (RoI) within 2.5 µs using the following independent sub-trigger systems.

**L1Calo** identifies the EM or hadronic clusters in the calorimeter. The local $E_T$ maxima are searched for.

**L1Muon** identifies the muon with muon trigger chambers, RPC, and TGC in the barrel and end-cap regions, respectively.

In HLT, a fast algorithm accesses the data from the RoI and the a full-event algorithm similar to the offline object reconstruction is performed within the average of 0.2 s. The events triggered by HLT are sent to the event storing infrastructure outside the ATLAS.

### 3.2.7 Luminosity Detector

The measurement of luminosity is very important for the normalization of the simulation to the recorded data set. The instantaneous luminosity is measured by the following formula:

$$\mathcal{L} = \frac{\mu_{vis} n_b f_b}{\sigma_{vis}},$$

where $n_b$ is the number of colliding bunch pairs and $f_b$ is the frequency of the beam circulation ($f = 11245.5$ Hz for LHC). $\sigma_{vis}$ is the total fiducial cross section of $pp$-interactions, including both the elastic and inelastic scatterings. $\mu_{vis}$ corresponds to the number of average interactions in a single bunch crossing. The following strategy is used to measure luminosity.

- Several detectors and algorithms are used to measure $\mu_{vis}$ via the inelastic rate.
- An absolute luminosity scale is calibrated by determining $\sigma_{vis}$.
- Systematic uncertainties are set by consistency of algorithms.

$\sigma_{vis}$ is provided by a dedicated calibration (van der Meer scan [51]), and $\mu$ is directly obtained from the rate information measured by the luminosity detector located in the very forward region near the beam pipe. The two following luminosity detectors contribute to the luminosity measurements.

**LUCID (Luminosity measurements Using Cherenkov Integrating Detector)** LUCID is located at the end of the ATLAS detector, 17 m away from the interaction point and covers pseudo-rapidity $5.6 < |\eta| < 6.0$. LUCID consists of 16 aluminum tubes filled with C$_4$F$_{10}$ and counts Cherenkov photons mainly kicked out by the charged particles generated in the $pp$ inelastic scattering at the interaction point.

**ALFA (Absolute Luminosity For ATLAS)** ALFA is located at $z = \pm 240$ m beyond the ATLAS envelope and sandwich beam pipe from top and bottom. The detector consists of 8 scintillation fibers.
Chapter 4
Monte Carlo Samples

All physics processes are simulated using the Monte Carlo (MC) method. To simulate physics of $pp$ collisions at the energy scale of $\mathcal{O}(\text{TeV})$, the description of QCD is required as well as the proton structure function which describes the momentum distributions of three valence quarks, sea quarks, and gluons surrounding them. The event simulation starts from a large momentum transfer between two partons in protons. Due to the asymptotic freedom of QCD, a parton can have a large momentum at one moment and be regarded as a free particle and described by perturbative QCD. The cross sections for the general physics processes, $pp \rightarrow X$, can be defined according to the factorization theorem:

$$
\sigma_{pp \rightarrow X} = \sum_{ab} \int dx_a dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \hat{\sigma}_{ab \rightarrow X}(x_a p_a, x_b p_b, \mu_R^2, \mu_F^2),
$$

(4.1)

where $a$ and $b$ are all possible partons to be summed over for $ab \rightarrow X$ processes. A parton distribution function (PDF), $f_i(x_i, \mu_F^2)$, represents the probability of a parton $i$ having a momentum fraction $x_i$ of the proton’s momentum at the scale $\mu_F$. The “generator” computes all possible Feynman diagrams for a certain physical interaction using the initial parton information. MC randomly simulates the initial/final states according to their probabilities. Thereafter, MC simulates the interaction between the generated particles and the full ATLAS detector material to process the simulated data equivalent to the real data. Finally, the simulated data is reconstructed in the same way as the real data.

4.1 HNL Event Generation

The MC samples for this analysis are generated using PYTHIA8 (v8.186) [52] and EvtGen (v1.6.0) [53] as generators with a model of $W^\pm$ production in 13 TeV $pp$ collisions, where NNPDF2.3 LO with A14 tune [54] is used as the PDF. $W^\pm$ is forced to decay into a muon and a custom-defined heavy neutral lepton (HNL, $N$); the HNL is given a long lifetime and set to decay half of the time into two muons and a neutrino and the remaining half of the time into a muon, an electron, and a neutrino. In both cases, the first muon comes from the mixing with the HNL and the second lepton, muon, or electron, comes from the decays of the virtual $W$. The simulated signal event diagrams are shown in Fig. 4.1. Individual HNL decay branching ratios are calculated to be $BR(N \rightarrow \mu\mu\nu) = 0.060$ and $BR(N \rightarrow \mu\nu\nu) = 0.106$, where the muon channel is lower due to the interference with the contribution from virtual $Z$. Thus, the total HNL decay branching ratio to the channels, which this analysis is sensitive to, is $BR(N \rightarrow \mu\mu\nu) + BR(N \rightarrow \mu\nu\nu) = 0.166$. 

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The coupling strength between the $W$ and $Z$ bosons of the weak interaction and an HNL is noted to be $|U|^2 = \Sigma_l |U_{lN}|^2$ (for $l = e, \mu, \tau$), where the terms $U_{lN}$ are the matrix elements for $N$ mixing with the different neutrino flavors. The signature considered in this search, which will be described in Chapter 6, is only sensitive to the mixing with $\nu_\mu$ and can thus constrain only $|U_{\mu N}|^2$, or $|U|^2$ in the case where $|U_{\mu N}|$ is dominant. The branching ratio for $W$ decays to an HNL and a charged lepton $l$ is directly proportional to the coupling strength $|U|^2$ and can be expressed as

$$BR(W \rightarrow N + l) = BR(W \rightarrow \nu + l) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right).$$

Its dependence on the HNL mass $m_N$ is not significant for $m_N < 30$ GeV (well below the $W$ mass $m_W$).

The HNL lifetime $\tau_N$ has a strong dependence on both the coupling strength $|U|^2$ and the mass $m_N$ and can be expressed as the following parameterization, which is accurate at the $1 - 2\%$ level in the mass range $5 - 50$ GeV (in s, considering $N$ mixing with $\nu_\mu$ and with $m_N$ in GeV):

$$\tau_N = 4.49 \cdot 10^{-12} |U|^{-2} m_N^{-5.19}.$$  

This relationship, however, assumes no lepton-number violating (LNV) decays. If LNV is allowed, for instance, in the case of a single Majorana neutrino, twice as many decay channels are opened, and the lifetime is reduced by a factor of 2.

The above relationships, together with estimates of efficiency with which ATLAS can reconstruct displaced vertices and reject related backgrounds, provide guidelines about the range of parameter space to which the search is sensitive. It corresponds to HNL masses around 10 GeV at the beginning of Run-2 (this analysis) and possibly up to 30 GeV at the end of Run-2.

Accordingly, different HNL masses $m_N$ are chosen for the simulations in the range where we expect sensitivity: 3, 5, 7.5, 10, 12.5, 15, 20, and 30 GeV. For each of these masses, a range of mean lifetimes $\tau$ corresponding to mean decay lengths $c\tau$ of 0.1, 1, 10, and 100 mm is generated.

### 4.2 Detector Simulation

The interaction between the particles generated by event generation and the detector material, and the detector responses of them are simulated by a full ATLAS detector simulation model.
based on the GEANT4 simulation [56]. Our samples are simulated using the full Geant-4 ATLAS simulation (FULLSIM) as our signature of a displaced decay is non-standard, i.e., of a type which usually justifies FULLSIM. The ATLAS has another simpler option for detector simulation called ATLAS fast simulation (ATLFAST). The difference with FULLSIM is that ATLFAST uses templates for calorimeter clusters instead of simulating the details of the showers, which should not affect our search significantly because we do not use specific calorimeter signatures beyond the need to identify electrons from their EM showers.
Chapter 5

Physics Object Reconstruction and Particle Identification

The low-level detector information is transformed to physics quantities through track reconstruction, identification and calibration. Although these procedures are also performed at the trigger level, the recorded events are refined by sophisticated off-line algorithms. The off-line reconstructed particles are referred to as physics “objects”.

5.1 Track and Vertex Reconstruction

Tracks and vertices are the most primitive and important physics objects. In this section, the newly developed reconstruction procedure for tracks and vertices displaced from the interaction point is described as well as the standard one.

5.1.1 Standard Track Reconstruction

A charged track is the basic element which can be the seed for various off-line particle reconstructions and calibrations. Therefore, track reconstruction is one of the most basic and important parts in physics analysis. The standard track, referred to as an “ID track” used in ATLAS is reconstructed with hits generated in the inner detector [57]. A Muon Spectrometer (MS) track for identifying a muon is reconstructed in a different way. Charged particles are generated in the beam collisions and pass through finely segmented detectors described in Sec. 3.1. In principle, the trajectory of a charged particle is reconstructed by connecting the points at which the hits are generated in the detectors. The trajectory of the charged particle draws a trajectory with a certain curvature due to the magnetic field in the detectors. When a charged particle with a transverse momentum $p_T$ passes through a uniform magnetic field $B$, the relation between $p_T$, $B$, and the orbital radius $R$ is described as

$$p_T \ [\text{GeV/c}] = 0.3 \cdot B \ [\text{T}] \cdot R \ [\text{m}].$$

From the viewpoint of track reconstruction, the ATLAS inner detector is composed of roughly two parts: fine-segmented silicon detectors (PIXEL and SCT) and thin long straw detectors (TRT). Similarly, there are two approaches for track reconstruction using the inner detector as summarized in Fig. 5.1. One approach is the main stream of track reconstruction with the inner detector. A
track seed is generated from space points which consist of sets ofPIXEL hits or SCT hits. Track seeds are extended to TRT hits. The other approach is a conservative stream. The TRT hits are extended to the silicon hits (outside-in).

**Inside-out Track Reconstruction**

The inside-out track reconstruction process is composed of the following four steps.

**Space Point Formation** The first step of inside-out track reconstruction is transforming the detector measurements to a three-dimensional point called “space point”. A space point is produced from the position information of the measurements on the detector surface and the position of the detector. It is easy to make a space point from the PIXEL which provides the two-dimensional information of its surface. Since the SCT is a silicon “strip” detector,
a precise measurement can be achieved only for the transverse direction. An SCT module consists of a pair of sensors tilted by 40 mrad and the measurements of both sides are used to form a space point. If a pair of SCT strip hits are obtained, the incident angle of the charged particle is roughly estimated. The rate of producing fake space points can be reduced by adding a constraint on the incident angle matching the direction from the beam interaction point to the space point.

**Space Point Seeded Track Finding** A track candidate is searched for by connecting the space points generated in the previous step. As the first step of the track seed search, three space points are connected. Once a track seed is found, then the track road building is performed, and further hits associated with the track are searched for. The track parameter of the candidate can be biased due to a coarse track candidate search procedure. Therefore, tracks are refitted using the combination of the standard Kalman filter \[58\] and a smoother. The Kalman filter, a linear quadratic estimation (LQE) method, is an algorithm which gradually estimates the unknown parameter with a set of measurements taking into account the statistical errors and other uncertainties.

**Ambiguity Solving** A vast number of track candidates are generated in the previous step. Almost all of these candidates are fake tracks accidentally reconstructed from non-related hits. To remove such track candidates, they are ranked in the order of the score corresponding to a likelihood. Before scoring the tracks, they are refitted using the further refined geometry information, and $\chi^2$ of the track fit divided by the number of degrees of freedom referred to as the reduced $\chi^2$ is obtained for each track. Not only the reduced $\chi^2$ but also track scoring strategy is used for scoring the tracks. In general, the rule of scoring is such that the track with a larger number of associated hits has a higher score. A track is imposed to a penalty when it has a hole defined as the detection layer on the trajectory of the track having no hit. When a track passes through the overlapped region of adjacent modules and has the hits from both of them, the track score has significantly extra points. When a hit is shared with different tracks, it is assigned to the track with a higher score and the other track is refitted without the shared hits. After iteration of these procedures, the tracks having scores above a certain quality cut are stored.

**TRT Track Extension** The tracks passing the ambiguity solving process are extended to the TRT measurements. To estimate if the hits on the TRT are compatible to the silicon track, a line fit is performed for the $r-\phi$ coordinates for the barrel region and $r-z$ coordinates for the end-cap regions. If the original score is higher than that after extension to TRT, the original one is stored and the TRT hits are treated as the outlier measurements of the track.

**Outside-in Track Reconstruction**

The inside-out track reconstruction process is optimized to find the tracks with a relatively high $p_T$ coming from the beam collision point. Therefore, particles from a secondary decay vertex of a long-lived particle such as $K^0_S$ or a photon conversion resulting in an electron-positron pair could fail in being reconstructed. Further, an electron losing its energy by bremsstrahlung fails in being reconstructed. Such tracks are the target for outside-in track reconstruction. The outside-in track reconstruction is performed in a similar flow as the inside-out procedure. Hough transformation is used to find TRT track hits. It transforms the positions of TRT hits on a track to the crossing line
5.1. TRACK AND VERTEX RECONSTRUCTION

in the parameter space. The crossing point specifies the actual parameters of the track line, and the point is determined by searching the peak position of a histogram which contains the lines in the parameter space. This approach works when the track can be approximated to a straight line in the $r$–$\phi$ plane for the barrel region and in the $r$–$z$ plane for the end-cap regions. In the 2016 data taking, the $p_T$ threshold of 2 GeV is applied to the outside-in track reconstruction. Finally, backward track reconstruction to the silicon hits is performed, and ambiguities are solved by the track scoring method.

5.1.2 Reconstruction of Tracks with Large Impact Parameters

The ATLAS standard track reconstruction is composed of two approaches: inside-out and outside-in. However, both of them are not efficient for hypothesized heavy long-lived particles because of the constraints on the longitudinal and transverse impact parameters ($z_0$ and $d_0$), which are defined as shown in Fig. 5.2. The tracks from the decays of heavy long-lived particles tend to have large impact parameters. A special track reconstruction procedure is developed to improve the reconstruction efficiency for the tracks with large impact parameters. This third method is based on the inside-out approach where leftover hits of the standard track reconstruction procedure are used for seeds. This track reconstruction is summarized in Fig. 5.3 and is called large-radius-tracking (LRT). The difference from the standard track reconstruction are as follows.

- The region where seeds are searched for is expanded.
- The cut for the transverse and longitudinal impact parameters are relaxed.
- The cuts on some quantities are optimized.

The cuts on the track parameters for different track reconstruction algorithms are compared in Table 5.1.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Inside-out</th>
<th>Outside-in</th>
<th>Large-radius tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max $</td>
<td>d_0</td>
<td>$</td>
<td>10 mm</td>
</tr>
<tr>
<td>Max $</td>
<td>z_0</td>
<td>$</td>
<td>250 mm</td>
</tr>
<tr>
<td>Min $p_T$</td>
<td>0.4 GeV</td>
<td>2 GeV</td>
<td>0.5 GeV</td>
</tr>
<tr>
<td>Min Pix hits</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Min Si hits</td>
<td>7</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Min TRT hits</td>
<td>9</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Min NOT Shared</td>
<td>6</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Max Shared</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Max Si Holes</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max PIXEL Holes</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Max SCT Holes</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max Double Holes</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: Cuts on track parameters applied in different track reconstruction algorithms (Max denotes “maximum”; Min denotes “minimum”).
Figure 5.2: Definition of the longitudinal and transverse impact parameters ($z_0$ and $d_0$).

Figure 5.3: Schematic view of large radius track reconstruction.
5.1. TRACK AND VERTEX RECONSTRUCTION

Figure 5.4: Displaced track reconstruction efficiency with and without large-radius tracking (LRT) for MC sample (HNL 5 GeV, $c\tau = 1, 10, 100$ mm sample are merged) as a function of radial distances of DVs ($r_{DV}$).

Track reconstruction efficiencies are compared in Fig. 5.4 as a function of the radial distance of a vertex ($r_{DV}$) from which the tracks originate. An efficiency drop is observed at $r_{DV} = 122$ mm is due to a gap in the PIXEL layer and the SCT layer. We also observe another efficiency drop at $r_{DV} = 300$ mm because of the minimum Si hits requirement.

### 5.1.3 Primary Vertex Reconstruction

The primary vertices (PVs) where $pp$ collisions occur is identified using the reconstructed ID tracks. PVs are reconstructed with the Iterative Vertex Finding algorithm [59, 60] by identifying the peak in the $z$ distribution of extrapolated tracks. The identified PV position is refined using an adaptive vertex fitting algorithm [61]. The ID tracks are then refitted using the reconstructed PVs. The procedure of re-fitting continues until all tracks are associated to either PVs, and the PVs with less than two associated tracks are discarded. Although 10–30 PVs are reconstructed per bunch crossing, it is usual that only one PV can cause meaningful scattering which fires the trigger. This PV, referred to as the “hard-scatter” vertex, is identified as the $p_T$ sum of associated tracks being the highest and its position is used as the origin of object calibration. The procedure of reconstructing PVs can be divided into vertex finding and vertex fitting. In the ATLAS experiment, an iterative method is used for the PV reconstruction. Tracks satisfying the following requirements are used for vertex reconstruction:
• $p_T > 400$ MeV,
• $|\eta| < 2.5$,
• the number of silicon hits (PIXEL + SCT) $\geq 9$ for $|\eta| \leq 1.65$, and $\geq 11$ for $|\eta| > 1.65$,
• the number of hits in IBL + B-Layer $\leq 1$,
• maximum one shared hit (one hit for PIXEL and two hits for SCT),
• the number of PIXEL holes $= 0$, and
• the number of SCT holes $\leq 1$.

The idea behind the procedure is the iterative algorithm using selected tracks.

1. The seed position of vertex fitting is chosen as the most probable value of the impact parameter $z_0$ for all tracks with respect to the beam line.

2. Tracks compatible to the seed are merged.

3. An adaptive vertex fitting algorithm using an annealing procedure is used to estimate the vertex position and its covariance with the seed position as the starting point and the selected track parameters as the input. The weights reflecting the compatibility of the estimated vertex and the annealing temperature parameter are assigned to each input track.

4. After generating a vertex candidate, the tracks which are still unassociated to any vertex are used to repeat the new vertexing procedure from the seeding step.

5.1.4 Displaced Vertex Reconstruction

Vertices displaced from the beam collision point are reconstructed with the VKalVert vertex reconstruction algorithm [62]. The input tracks in this algorithm are required to satisfy the following criteria:

• the number of SCT hits $\geq 2$,
• $p_T > 1$ GeV,
• $|d_0| > 2$ mm, and
• $\leq 2$ PIXEL hits or $> 0$ TRT hit.

First, the algorithm generates a “seed” vertex which consists of two tracks with the incompatibility graph method [63]. The seed vertex is required to have good fitting quality ($\chi^2/N_{dof} < 5$, for the seed vertex, $N_{dof}$ is always 1). Some requirements are applied to these seed vertices to remove fake vertices. The certain hit patterns in the PIXEL and SCT are required for the tracks associated with the seed vertices. The hit pattern depends on the position of a reconstructed vertex. If the vertex contains a track which has hits inside the vertex position, the vertex is regarded as fake and is removed. The track is also required to have a hit in a neighbor layer with a larger radius. If the vertex is reconstructed near a layer of silicon detectors, a hit is required in the next
outer layer but not required in the next inner layer. For producing all possible N-track vertices with the surviving seed vertices, an incompatibility graph is applied. At this point, it is allowed that the same track is used in more than one vertex. Therefore, the following iterative “clean up” algorithm is applied.

1. Finding the combination of vertex + track which has the largest \( \chi^2 \) among all tracks used in more than one vertex.

2. Removing the tracks if the \( \chi^2 \) is greater than 6 or two vertices are displaced by more than 3 \( \sigma \).

3. Otherwise, the two vertices are merged and fitted to obtain vertex parameters.

4. Return to step 1.

5. Continuing the above steps until there are no shared tracks among vertices and then merging a vertex pair where the distance is less than 1 mm and re-fitting.

The reconstruction efficiency of the displaced vertices is shown in Fig. 5.5.
5.2 Electron Reconstruction and Identification

Electrons are reconstructed using the deposited energy measured in ECAL and the tracks are reconstructed in the inner detector. As a first step, a seed EM cluster is considered as an electron candidate in the cluster window of $3\times5$ with the unit of $\Delta\eta \times \Delta\phi = 0.25 \times 0.25$ at the middle layer of ECAL. The measured energy clusters are made by merging the energy deposits. This cluster reconstruction has an efficiency of 95% for $E_T = 7$ GeV and above 99% for $E_T > 15$ GeV. Because electrons leave tracks in the inner detector, track-to-cluster matching is performed to identify a cluster as an electron candidate. The electron candidates are further evaluated to remove fake electrons and electrons from pile-up PVs using the following criteria:

- $p_T \geq 7$ GeV,
- $|\eta| \leq 2.47$,
- $|d^0_{BL}/\sigma^0_{BL}| < 5$,
- $|(z^0_{BL} - z^{VTX})\sin\theta| < 0.5$ mm,

where $\eta$ is calculated with respects to the cluster position at the second layer of ECAL, and $d^0_{BL}$ ($z^0_{BL}$) is the transverse (longitudinal) impact parameter with respect to the beam line. $\sigma^0_{BL}$ is an uncertainty of $d^0_{BL}$, and $z^{VTX}_{0}$ is the vertex position in the $z$-axis. The electron ID algorithm adopted here is the likelihood-based (LH) method using the probability density functions (PDFs) of variables listed in Table 5.2. The discriminant is calculated as

$$d_L = \frac{L_s}{L_s + L_b}, \quad L_{s(b)} = \prod_i P_{s(b),i}. \quad (5.2)$$

Three operating points (tightLH, mediumLH, looseLH) are provided depending on $p_T$ and $\eta$ for each $d_L$.

The electron reconstruction algorithm performs the following procedure.

**Reconstruction of an EM cluster from the energy deposit in the ECAL** This is performed by the sliding window algorithm. Cells in all the four layers in the ECAL are grouped into $\eta \times \phi$ towers of $0.25 \times 0.25$, and the window defined in a unit of $3 \times 5$ is slided over the detector. A local maximum of energy in the window more than 2.5 GeV is identified as an EM cluster. 95% (99%) of clustering efficiency is maintained for electrons with $E_T = 7$ GeV ($> 15$ GeV).

**Track-Cluster matching and refitting** EM clusters are matched with ID tracks. If multi-tracks satisfy the matching criteria, the track which has the closest $\Delta R$ to the EM cluster is selected. The matched tracks are re-tracked with the Gaussian Sum Fitter (GSF) algorithm [64], where the bremsstrahlung is modeled.

**Energy determination** The track momentum and calibrated EM cluster energy are merged with a multi-variable algorithm for better energy determination.
The reconstructed electron candidates are dominated by the background of pions in jets especially for low-$E_T$. Therefore, a powerful identification algorithm is adopted where a multi-dimensional likelihood exploiting all relevant detector information is used. 20 variables in total are listed in Table 5.2 and are used for the likelihood including the longitudinal or transverse EM shower profiles and the number of TRT high-threshold hits.

Displaced electrons are also defined in which the discriminant of $d_0$ is not used. The electron reconstruction efficiency is defined as the probability of a electron being reconstructed when its ID track is reconstructed is shown in Fig. 5.6. The electron reconstruction efficiency is high and does not depend on the radial position of a vertex which the electron coming from. The electron identification efficiency is defined as the probability of being identified as loose, medium, or tight electrons for reconstructed electrons for each quality criterion (tightLH, mediumLH, looseLH) and are compared as a function of $r_{DV}$ in Fig. 5.7.

Figure 5.6: Distribution of displaced electron reconstruction efficiency as a function of a radial distance of a vertex (HNL 5 GeV, $c\tau = 1, 10, 100$ mm sample are merged).

### 5.3 Muon Reconstruction and Identification

Muons are reconstructed independently from ID tracks and referred to as MS tracks. The tracking starts from finding hits in the MDT/CSC chambers and then forming a small track segment in each chamber. Hough transformation is used to convert the bending detector plane geometry to a flatten plane. A line fit is performed on the flatten plane towards track segments. The hits in RPC and TGC are used to determine the coordinate orthogonal to the MDT/CSC detector plane. A search algorithm uses a loose requirement of compatibility between track segments and hits by
taking into account the energy loss due to the muon interaction with the material. The trajectory and momentum of muons are determined by the synergy between the reconstructed track and the measurements in other detectors. There are four different types of muons.

**Combined Muon** Such muons have tracks in both MS and ID. A combined track is formed with a global fit that uses the hits from the ID and MS subdetectors. During the global fit procedure, the MS hits may be added or removed from the track to improve the fit quality. Most muons are reconstructed by outside-in pattern recognition in which MS tracks are extrapolated inward and are matched to an ID track while inside-out combined reconstruction is used as a complementary approach.

**Segment-tagged Muon** Fragments of an MS track are matched to an ID track. When an ID track is extrapolated to the MS, it is classified as a muon if it is associated with at least one local track segment in an MDT or CSC chamber.

**Standalone Muon** An MS track which is outside the acceptance of the inner detector ($2.5 < |\eta| < 2.7$).

**Calorimeter-tagged Muon** This is a special reconstruction for a muon traveling the non-sensitive region for MS ($|\eta| < 0.1$). ID tracks with $p_T > 15$ GeV are associated to the energy deposit in the calorimeter equivalent to the minimum ionizing particles.
Similar to electrons, three operating points (tight, medium, loose) are provided depending on the types of muons.

**Loose** Loose identification criteria are designed to maximize the reconstruction efficiency while providing good-quality muon tracks. All combined and standalone muons are regarded as loose muons. Segment-tagged and calorimeter-tagged muons are required to satisfy $|\eta| < 0.1$.

**Medium** Medium identification criteria is the default selection for muon in ATLAS. This selection minimizes the systematic uncertainties associated with muon reconstruction and calibration. Only combined and standalone muons are used. For combined muons, $\geq 3$ hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. Standalone muons are required to have at least three MDT/CSC layers and are employed only in the $2.5 < |\eta| < 2.7$ region to extend the acceptance outside the ID geometrical coverage.

**Tight** Tight muons are selected to maximize the purity of muons losing some efficiency. Only combined muons can be regarded as tight muons. In addition to the medium selection criteria, hits in at least two stations of the MS are also required. The normalized $\chi^2$ of the combined track fit is required to be less than 8 to remove pathological tracks. A two-dimensional cut in the $\rho'$ and $q/p$ significance variables is performed as a function of the muon $p_T$ to ensure stronger background rejection for momenta below 20 GeV, where the misidentification probability is higher.

Here, $q/p$ significance is defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in the quadrature of the corresponding uncertainties. $\rho'$ is defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the $p_T$ of the combined track ($\rho' = |p_T^{ID} - p_T^{MS}|/p_T^{CB}$).

The displaced muons are also defined where ID tracks reconstructed by LRT are allowed. Muon reconstruction efficiency which is defined as a probability of a muon reconstructed when its ID track is reconstructed is shown in Fig. 5.8. The muon reconstruction efficiency is high and does not depend on the radial position of a vertex which the muon coming from. The displaced muon identification efficiencies, defined as the probability of being identified as each quality (loose, medium tight) muon for reconstructed muons are compared as a function of $r_{DV}$ in Fig. 5.9.
Figure 5.8: Distribution of displaced muon reconstruction efficiency as a function of a radial distance of a vertex (HNL 5 GeV, \( c\tau = 1, 10, 100 \) mm sample are merged).
<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic leakage</td>
<td>Ratio of $E_T$ in the first layer of the hadronic calorimeter to $E_T$ of the EM cluster (used in $</td>
</tr>
<tr>
<td></td>
<td>Ratio of $E_T$ in the hadronic calorimeter to $E_T$ of the EM cluster (used in $0.8 &lt;</td>
</tr>
<tr>
<td>Back layer of EM calorimeter</td>
<td>Ratio of the energy in the back layer to the total energy in the EM calorimeter. This variable is used only below 100 GeV of $E_T$ because of the physical back layer leakage at higher energies</td>
</tr>
<tr>
<td>Middle layer of EM calorimeter</td>
<td>Lateral shower width, $\sqrt{\left(\sum E_i \eta_i^2\right) / \left(\sum E_i \right) - \left(\sum E_i \eta_i\right)^2 / \left(\sum E_i\right)^2}$, where $E_i$ is the energy of cell $i$ at pseudo-rapidity $\eta_i$. The sum is calculated within a window of 3 $\times$ 5 cells.</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy difference between the largest and the second largest energy deposits in the 3 $\times$ 5 cells</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in the strip layer to the total energy in the EM calorimeter</td>
</tr>
<tr>
<td>Strip layer of EM calorimeter</td>
<td>Shower width, $\sqrt{\left(\sum E_i (i - i_{max})^2\right) / \left(\sum E_i\right)}$, where $i$ runs over all strips in a window of $\Delta \eta \times \Delta \phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in $\eta$, and $i_{max}$ is the index of the highest-energy strip.</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter</td>
</tr>
<tr>
<td>Track conditions</td>
<td>Number of hits in the innermost PIXEL layer to discriminate against photon conversions</td>
</tr>
<tr>
<td></td>
<td>Number of hits in the PIXEL detector</td>
</tr>
<tr>
<td></td>
<td>Number of total hits in the PIXEL and SCT detectors</td>
</tr>
<tr>
<td></td>
<td>Transverse impact parameter with respect to the beamline</td>
</tr>
<tr>
<td></td>
<td>Significance of transverse impact parameter defined as the ratio $d_0$ and its uncertainty</td>
</tr>
<tr>
<td></td>
<td>Momentum lost in the track between the perigee and the last measurement point divided by the original momentum</td>
</tr>
<tr>
<td>TRT</td>
<td>Likelihood probability based on transition radiation in the TRT</td>
</tr>
<tr>
<td>Track-cluster matching</td>
<td>$\Delta \eta$ between the cluster position in the strip layer and the extrapolated from the perigee</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi$ between the cluster position in the middle layer and the track extrapolated from the perigee</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi_2$, similar to $\Delta \phi$ but the track momentum is re-scaled to the cluster energy before extrapolating the track from the perigee to the middle layer of the calorimeter</td>
</tr>
<tr>
<td></td>
<td>Ratio of the cluster energy to the track momentum</td>
</tr>
</tbody>
</table>

Table 5.2: Definitions of electron discriminating variables [65].
Figure 5.9: Displaced muon identification efficiency for each quality criterion (HNL 5 GeV, $c\tau = 1, 10, 100$ mm sample are merged).
The goal of this chapter is to define a signal region and control regions for estimating the contributions of background events to the signal region. The properties of our signal, expected background sources, and event selection are discussed. The event selection includes pre-selections like a trigger selection and a derived raw data (DRAW) filter and vertex selections which are optimized to reduce background events.

The event flow of this analysis is shown in Fig. 6.1. The first stage of the event selection is the trigger selection described in Sec. 3.2.6, which chooses interesting events to reconstruct. The second step of our event selection is the DRAW filter which is designed for performing a dedicated reconstruction. At the last stage of the selection, a displaced vertex which has signal-like properties is required using Analysis Object Data (AOD) as described in Sec. 6.5. A concise summary of the selection criteria for the DRAW filter, the signal region, and the background control regions is provided in Table 6.1.

![Figure 6.1: Schematic view of the event flow in this analysis.](image)

### 6.1 Signal Process

As discussed in Sec. 2.4.2, the HNLs are assumed to be produced from $W$ boson decays in the ATLAS detector. The $W$ boson production at a very high rate in the LHC allows us to search for the HNLs with high sensitivity. The production and decay diagrams of the HNLs are shown in
Table 6.1: Summary of the DRAW filter and DV selection criteria for the definition of the signal region, the control region, and the validation region for the background estimate. The signal region, control region, and two validation regions are referred to as regions A, C, A’, and C’, respectively.

Table 6.1:

<table>
<thead>
<tr>
<th>Region/filter</th>
<th>Object</th>
<th>Selection criteria</th>
</tr>
</thead>
</table>
| DRAW filter (Section 6.3) | trigger prompt muon displaced muon | *HLT* mu26_iwarmmedium combined, $p_T > 28$ GeV, $|\eta| < 2.5$, $p_T^{\text{cone}30}/p_T < 0.005$  
$p_T > 5$ GeV, $|\eta| < 2.5$, $p_T^{\text{cone}30}/p_T < 1$,  
StandAlone/SegmentTagged muon OR  
Combined muon with $\chi^2/\text{dof} > 5$ OR ($\chi^2/\text{dof} < 5$ AND $|d_0| > 0.1$) |
| Signal (A) (Section 6.6.1) | filter prompt muon DV | pass the DRAW filter  
tight, $|d_0^{BL}\text{significance}| < 3$, $|\Delta z^{BL}\sin\theta| < 0.5$ mm  
fiducial volume: $4$ mm $< r_{DV} < 300$ mm  
2-track vertex with opposite charges  
tight muon in vertex  
second tight lepton ($e$ or $\mu$) in vertex  
cosmic veto: $\sqrt{(\Sigma \eta)^2 + (\pi - \Delta \phi)^2} > 0.04$  
$m_{DV} > 4$ GeV |
| Control (C) (Section 6.6.2) | filter DV | pass DRAW filter  
the same as signal, but with same charge tracks in vertex |
| Validation (A’,C’) (Section 6.6.3) | filter DV | pass DRAW filter  
the same as signal and control, but only one tight lepton in vertex |

Fig. 6.2. An HNL is produced from an on-shell $W$ boson as a decay product and a charged lepton is produced simultaneously. The HNL is supposed to decay to a charged lepton and an off-shell $W$ boson, which decays to a charged lepton and a neutrino or two quarks. Due to the HNL’s long lifetime, the decay products of the HNL make a vertex which is displaced from the interaction point of the $pp$ collisions. For simplicity of triggering and reconstruction of physics objects, we restrict ourselves to a channel in which the charged leptons from the on-shell $W$ and the HNL are muons and the off-shell $W$ decays to an electron or a muon and a neutrino (Fig. 6.2 (right)). This means that we ignore cases in which the on-shell $W$ and HNL decay to an electron or a tau lepton and the off-shell $W$ decays hadronically. These events can contaminate our signal region and will be defined in Sec. 6.6.1.

![Figure 6.2](image.png)  
Figure 6.2: Production and decay diagrams for the HNL (left) and for this analysis (right). The HNL illustrated as dotted lines are produced as decay products of $W$ bosons and decay to leptons and off-shell $W$ bosons. As a final state to analyze, we assume one prompt muon and two leptons which construct a displaced vertex.
6.2 Trigger Selection

Trigger is the first step of the event selection. The signal event includes a prompt muon as shown in Fig. 6.2 and it is used for triggering signal-like events. The trigger used in this analysis is \textit{HLT\_mu26\_ivarmedium} which requires a single muon with transverse momentum more than 26 GeV as described in Ref. [66]. A medium selection of isolation is also required in the trigger. As a requirement for the muon isolation, there is a cut on the scalar sum of $p_T$ values of tracks within a cone around the muon candidate which has a muon $p_T$ dependent size.

6.3 DRAW Filter

In this analysis, events which pass the single muon trigger are filtered by the DRAW filter. This filter is designed for this analysis in which “non-standard” reconstruction such as the large-radius tracking described in Sec. 5.1.2 is required. It allows high signal efficiency and a reduction of the data processing rate to the level of a few Hz in order to save computing load and data storage for the computer-intensive procedure. Then, it produces DRAW data samples used by analyses with unconventional signatures. The DRAW filter for each analysis is optimized to suit each signature to seek for. Our DRAW filter requires the prompt muon which is thought to be coming from $W$ boson decays with the following properties:

- combined muon,
- $p_T > 28$ GeV,
- $|\eta| < 2.5$, and
- $p_{T\text{cone}30}/p_T < 0.05$.

Here, $p_{T\text{cone}30}$ is a track-based isolation variable which requires that other particles do not exist around the target particle to remove muons from jet decays. It is defined as the sum of the transverse momenta of the tracks with $p_T > 1$ GeV in a cone of size $\Delta R = 0.3$ around the muon transverse momentum, excluding the muon track itself.

In this filter, a second muon is also required. For the second muon, since we expect it to come from a displaced vertex, the following requirements are applied.

- $p_T > 5$ GeV,
- $|\eta| < 2.5$,
- $p_{T\text{cone}30}/p_T < 1$, and
- the muon should either be a standalone or combined muon described in Sec. 5.3. If it is a combined muon, it should have either $|d_0| > 0.1$ mm or $|d_0| < 0.1$ mm and $\chi^2/N_{\text{dof}} > 5$. 
6.4 Background Sources

The final state of our signal consists of a prompt muon and a displaced vertex which includes two leptons having opposite-sign electric charges. No SM particle can make such a signature. Therefore, we expect very low backgrounds in our signal region. Although these are very rare processes, there are some background sources which can mimic our signal vertex. The sources of background events are investigated in this section.

6.4.1 Metastable Particles

There are some SM particles produced in the LHC $pp$ collisions which have relatively longer lifetimes and then have decay lengths near our signal region. Beauty, charm, and strange hadrons can contaminate our signal region and their lifetimes and masses are shown in Fig. 6.3.

Strange baryons have lifetimes of $O(10^{-10})$ s close to the signal region and they have masses between 1 and 2 GeV. However, strange baryons almost always decay into hadrons; thus, its decay products do not make a lepton vertex. This motivates tight lepton identification in a displaced vertex as a part of the event selection.

Bottom hadrons have masses of $5 - 6$ GeV and lifetimes of the order of $10^{-12}$ second. They can have a few mm decay length when they are highly boosted and/or in the tail of the exponential decay distribution. The decay products of bottom hadrons cannot be a two-lepton vertex except for its decays to $J/\psi$ or $\psi(2S)$ decaying into a lepton pair. $J/\psi$ and $\psi(2S)$ have masses of 3.1 GeV and 3.7 GeV, respectively. Their contributions are discussed in Sec. 6.5.4.

The $\Upsilon$ mesons are massive particles which can decay into a lepton pair. Its production cross section is much smaller, and its lifetime is very short. Its mass is about 10 GeV and higher than bottom hadrons, and so it cannot be produced from the bottom hadron decays. Thus, we do not expect it to give rise to a displaced vertex.

6.4.2 Hadronic Interactions in Material

Hadrons produced in the LHC $pp$ collisions can interact with the detector material and such interactions can produce several charged hadrons. These hadrons will be reconstructed as a vertex at some distance from the interaction point, thus faking displaced vertices. These effects are discussed in Sec. 6.5.5.

6.4.3 Cosmic Ray Backgrounds

A cosmic ray muon which crosses the detector close to the interaction point can be reconstructed as two back-to-back displaced muons. If a cosmic ray muon is reconstructed as a two-muon displaced vertex, it is regarded as a high mass vertex due to the apparent large opening angle of the two muons.

6.4.4 Random Track Crossing

Random Track Crossing (RTC) happens when two random and uncorrelated tracks accidentally cross in the inner detector sufficiently close to each other such that the vertexing algorithm associates them with a common vertex. Since the LHC is running in a high pile-up environment, such
6.5 Displaced Vertex Selection

Although requiring the displaced vertex to consist of two opposite-sign leptons is a powerful selection to suppress the background events, there are some sources which can make/mimic a two-lepton displaced vertex as discussed in Sec. 6.4. To reduce the contributions from such events, we apply some requirements to the reconstructed displaced vertices. In this section, the vertex selections which are applied to the signal region are described.

Figure 6.3: The lifetimes and the masses of the standard model particles which have relatively longer lifetimes.

The contribution of RTC is estimated by a data-driven method with all other backgrounds as described in Chapter 7.
6.5.1 Fiducial Volume Cut

The position of a displaced vertex is required to be in the fiducial volume which is defined as the region with \( r_{DV} < 300 \) mm and \( |z_{DV}| < 300 \) mm where \( r_{DV} \) and \( z_{DV} \) denote radial and longitudinal distances of a displaced vertex, respectively. This region corresponds to the region which is covered by the first barrel layer of the SCT in \( r_{DV} \) and the first barrel layer of the PIXEL (IBL) in \( |z_{DV}| \). This is a crucial claim for tracks reconstructed by the large-radius tracking due to its requirement of the number of silicon hits.

6.5.2 DV Displacement Cut

The vertex should be displaced by at least 4 mm in the \( x-y \) plane from the interaction point (\( r_{DV} > 4 \) mm). This cut is used to reduce vertices made by the Standard Model particles which have relatively short lifetimes, such as bottom hadrons and \( \tau \) leptons.

6.5.3 Cosmic Ray Muon Veto

To reduce the cosmic ray muon backgrounds, a distinctive feature of the vertex made by a cosmic ray muon is used. Because it is actually just one track reconstructed as two tracks, these two tracks should be back-to-back. To evaluate the opening angle between them, the following variable is defined:

\[
\Delta R_{\text{cos}} = \sqrt{(\eta_1 + \eta_2)^2 + (\pi - |\phi_1 - \phi_2|)^2}.
\]  

This variable becomes close to zero when two tracks are back-to-back. For a high statistic control region in which an absence of the prompt muon is required, the number of the two muon vertices are plotted in Fig. 6.4 as a function of \( \Delta R_{\text{cos}} \) for high mass (> 50 GeV) and low mass (< 50 GeV) vertices separately. Because no standard model process makes a two-muon vertex with more than 50 GeV mass, these vertices are thought to be cosmic ray muon vertices. High mass vertices have a peak around 0 and low mass vertices have non-zero values. The requirement of \( \Delta R_{\text{cos}} > 0.04 \) is enough to reduce the cosmic ray background, while few signal events are rejected by this cut (Fig. 6.5).

![Figure 6.4: Distributions of \( \Delta R_{\text{cos}} \) for high mass (> 50 GeV) vertices (red) and low mass (< 50 GeV) vertices (blue) for the whole range (left) and for around \( \Delta R_{\text{cos}} = 0 \) (right).](image)
6.5. DISPLACED VERTEX SELECTION

![Graph showing distributions of $\Delta R_{\cos}$ for different HNL masses.](image)

Figure 6.5: Distributions of $\Delta R_{\cos} = \sqrt{(\eta_1 + \eta_2)^2 + (\pi - |\phi_1 - \phi_2|)^2}$ for signal MC for the different HNL masses. Few events are distributed around $\Delta R_{\cos} = 0$, and the cosmic ray veto rejects few signal events.

### 6.5.4 DV Mass Cut

Applying a mass cut to the displaced vertices is effective to reduce the backgrounds because the standard model particles which have enough long lifetime to contaminate our signal region have relatively small masses. The displaced vertex masses are calculated as $m_{DV} = \sqrt{(\Sigma E_i)^2 - (\Sigma p_i)^2}$ and are reconstructed assuming the pion mass for each reconstructed particle irrespective of its type. We set this cut at 4 GeV to avoid the contribution from $J/\psi$ and $\psi(2S)$ as the decay products of bottom hadrons, which we assume to be the highest massive particles which can contaminate our signal region.

The contribution from $J/\psi$ and $\psi(2S)$ is studied by identifying peaks around their masses of 3.1 GeV and the 3.7 GeV in a high-statistics control sample in which there is no prompt muon, using events selected by other DRAW filters. This enhances the number of events by a factor 10. Fits are performed to both peaks as shown in Fig. ?? (left) with Gaussian functions. The intrinsic mass distribution should follow Breit-Wigner functions, but the decay widths of the $J/\psi$ and $\psi(2S)$ peaks are much narrower than the detector resolution. Thus, the widths of peaks are then dominated by detector resolution and the Gaussian function is used as a fitting function.

The area under the fitted function for $m_{DV} > 4$ GeV is $O(10^{-22})$ event, confirming that the resolution is good enough to result in negligible contributions from these resonances in the signal region. The shape of the vertex distance distribution for $J/\psi$ DV candidates shows that most of them appear at short distances consistent with production by boosted $B$-hadron decays although a suppression is observed at very short distances which is likely due to the track $|d_0| > 2$ mm requirement in the vertexing algorithm (Fig. 6.6, right).
Figure 6.6: Distribution of reconstructed two-muon displaced vertices masses around $J/\psi$ (3.1 GeV) and $\psi(2S)$ (3.7 GeV) masses (left). These two peaks are fitted with Gaussian functions. To verify the origin of their peaks, the distribution of the reconstructed radial distances for displaced vertices with masses of $3.0 < m_{DV} < 3.2$ GeV is plotted (right).

### 6.5.5 Material Veto

Hadronic interactions with the inner detector material can be the source of background displaced vertices. In another analysis using displaced vertices [67] prepared a three-dimensional map and it was used as the map to veto vertices made by hadron interactions. Two-dimensional maps of the number of vertices which are located in the material region projected in the $x$-$y$ plane are shown in Fig. 6.7. The map covers the whole fiducial volume of $r_{DV} < 300$ mm, $|z_{DV}| < 300$ mm, and the full $2\pi$ for the transverse plane.

The complicated parts of the map such as the structure of the PIXEL modules are made from the actual vertices distribution reconstructed in minimum bias data while for the map of simpler and uniform parts, e.g., support rings, geometrical approximations are performed.

The slight movement of the detector due to its weight should be accounted for when approximating the position of the beam pipe, for instance. The dataset taken in 2016 is used to ensure their positions are appropriate for the analysis. The exact positions of the geometry augmented by this effect are found in Table 6.2. The total volume in the material map is 42% of our fiducial volume.

<table>
<thead>
<tr>
<th>Material layer</th>
<th>Radius</th>
<th>Thickness</th>
<th>$x$ offset</th>
<th>$y$ offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>24 mm</td>
<td>3 mm</td>
<td>0 mm</td>
<td>-1.5 mm</td>
</tr>
<tr>
<td>PIXEL support 1</td>
<td>29 mm</td>
<td>1.6 mm</td>
<td>-0.3 mm</td>
<td>-0.5 mm</td>
</tr>
<tr>
<td>PIXEL support 2</td>
<td>42.5 mm</td>
<td>2.4 mm</td>
<td>-0.2 mm</td>
<td>-1 mm</td>
</tr>
<tr>
<td>PIXEL support 3</td>
<td>68.5 mm</td>
<td>4.5 mm</td>
<td>-0.1 mm</td>
<td>-0.5 mm</td>
</tr>
</tbody>
</table>

Table 6.2: Approximations of uniform shapes augmented by the offsets created due to the decoupling of the beam pipe from the ATLAS cavern.

To study the effects of the hadronic interactions with the detector material, the $m_{DV}$ distributions are compared between the low-density material region and the high-density material region.
6.5. DISPLACED VERTEX SELECTION

Figure 6.7: Number of vertices which are located in the inner detector region.

defined in the material map. The reconstructed mass \( m_{DV} \) distribution for such vertices peaks at below 1 GeV, as observed in Fig. 6.8. For \( m_{DV} > 2.5 \) GeV, the two distributions follow the same shape, clearly indicating that the vertices in this range are dominated by other processes. When we apply mass cut on 4 GeV, we can ignore the effects from the hadronic interactions.

Other parameters such as the vector sum of the two tracks’ \( p_T \) in a displaced vertex and \( \Delta R = \sqrt{(\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2} \) of the two tracks in the vertex are also compared between the low-density material region and the high-density material region before and after the mass cut (Figs. 6.9 and 6.10). It is clear that the difference between the distribution of each region becomes smaller after the mass cut.

There is, however, a possibility that a track from hadronic interaction crosses by an unrelated track at a large angle, leading to a high mass vertex. In the vast majority of the cases, the vertices are made of hadrons. Those background displaced vertices are efficiently rejected by a lepton identification criterion, although hadrons can be misidentified as leptons and in rare cases, hadrons that decay into lepton pairs (such as \( \rho, \omega \) and \( \phi \)) can be produced. The background from RTC is estimated by a data-driven method and hadron vertices misidentified as leptons can be rejected by the mass cut.

A comparison of the vertex mass distribution in the low-density and the high-density regions for the one-lepton vertex is shown in Fig. 6.11. The contribution from hadronic interaction is clearly visible in high-density region at low masses.
6.6 Region Definition

The background sources discussed so far can be suppressed to a negligible level by appropriate event selection. In a signal region, enriched HNL events and suppressed background events should be obtained. Such a signal region is defined by these sections and the control regions are also defined for estimating the number of remaining background events in the signal region. The validation regions are defined to validate our data-driven background method described in Chapter 7. The definition of the regions and selections are summarized in Fig. 6.12.

6.6.1 Signal Region

A region in which the HNL events are enriched is defined as the signal region A. First, a prompt muon is required in the signal region, which passes the following criteria as well as those required in the DRAW filter.

- tight combined muon,
- $|d^\text{BL}_0^0|/\sigma_{d^\text{BL}_0^0} < 3$, and
- $|\Delta z^\text{BL}_0^0 \sin \theta| < 0.5$.

A signal event also has a displaced vertex with two leptons (either $\mu\mu$ or $\mu e$) and to remove the background vertices, the requirement discussed below are necessary:

- $4 \text{ mm} < r_{DV} < 300 \text{ mm},$
- two tracks with opposite sign charges,
- two tight muons or one tight muon and one tight electron,
Figure 6.9: The vector sum of $p_T$ for tracks in a displaced vertex is compared between the low density region and the high density region before (left) and after (right) the mass cut on 4 GeV. Their ratios are also shown (bottom).

- $\Delta R_{\cos} = \sqrt{(\Sigma \eta)^2 + (\pi - \Delta \phi)^2} > 0.04$, and
- $m_{DV} > 4$ GeV.

The set of the selections for the signal region except for the requirements of charges and the number of leptons in a DV is referred to as baseline selection.

### 6.6.2 Control Regions

The control regions to estimate the number of background events in the signal region also requires the same criteria as the signal region except for the electric charge sign of the two tracks in a displaced vertex. The same sign vertices are required in the control regions assuming that the backgrounds from metastable particles are negligible thanks to the mass cut, and then the components of background sources are dominated by RTC as the signal region.

### 6.6.3 Validation Regions

Our data-driven background method is evaluated using the validation regions with less signal contamination. The validation regions are chosen as the events passing all the signal region and control region criteria except for the number of leptons in the vertex. Both the vertices consist of...
Figure 6.10: Distribution of $\Delta R$ for low density region and high density region before (left) and after (right) mass cut on 4 GeV. Their ratios are also shown (bottom).

one muon and one non-lepton track, and one electron and one non-lepton track are defined as the validation regions (A’ and C’).
6.6. REGION DEFINITION

Figure 6.11: Distribution of the displaced vertex masses ($m_{DV}$) for a muon + a nonlepton track vertex (left) and an electron + nonlepton track vertex (right).

Baseline selection

Pre-selection
- trigger (HLT_mu26_ivamedium)
- DRAW Filter

Prompt muon
- tight combined muon
- $|d_0^{BL}/\sigma_d| < 3$
- $|\Delta z_{0}^{BL}\sin\theta| < 0.5$

Displaced vertex
- 2 tracks
- within the fiducial volume ($4 \text{ mm} < r_{DV} < 300 \text{ mm}$, $|z_{DV}| < 300 \text{ mm}$)
- cosmic veto ($\sqrt{(\Sigma\eta)^2 + (\pi - \Delta\phi)^2} > 0.04$)
- $m_{DV} > 4 \text{ GeV}$

Opposite sign
- 2 tight lepton: Signal (A)
- 1 tight lepton: Validation (A')
- no lepton: Control (B)

Same sign
- 2 tight lepton: Signal (C)
- 1 tight lepton: Validation (C')
- no lepton: Control (D)

Figure 6.12: Selection flows.
Chapter 7

Data-Driven Background Estimation

Almost all background events mentioned in Sec. 6.4 can be rejected by the event selection discussed in Sec. 6.5. The number of remaining background events, mainly from random track crossing, is estimated by a data-driven method. In this chapter, the method of estimating the background events which pass all our selections and end up in our signal region is described, and the number of background events is calculated using this method. A validation of this method is performed using the less signal contamination regions, so called validation regions. The signal, control and validation regions defined in Sec.6.6 are summarised in Table. 7.1 and the number of observed events in each region is shown in it.

<table>
<thead>
<tr>
<th>Number of leptons in DV</th>
<th>Same sign charge DV</th>
<th>Opposite sign charge DV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>C:0</td>
<td>A:0</td>
</tr>
<tr>
<td>1 ($\mu$)</td>
<td>C':83</td>
<td>A':89</td>
</tr>
<tr>
<td>1 ($e$)</td>
<td>C':28</td>
<td>A':35</td>
</tr>
<tr>
<td>0</td>
<td>D:169254</td>
<td>B:168037</td>
</tr>
</tbody>
</table>

Table 7.1: The definition of the signal (A), control (B,C,D) and validation (A',C') regions. Each region is distinguished by the number of leptons and signs of two tracks in a displaced vertex.

7.1 Description of Method

This analysis adopts a blind analysis in which the signal region is blinded and the contribution of background events to the signal region is estimated using the control regions where the events in them are well understood. The control regions can be defined as regions reversing a selection cut for the signal region. For this analysis, regions which passes all selection cuts except for the signs of two tracks are chosen as the control regions. In this method, it is assumed that the ratio of the number of two lepton DVs to that of two non-lepton track DVs is independent of the signs of these tracks. In other words, we assume the ratio $A/B$ equals to $C/D$ and then the number of background events is calculated as $BC/D$. The same sign control region C provides an unbiased estimate of all backgrounds in the signal region A except for the background decays from neutral metastable particles. The decay products from neutral particles are predominantly opposite sign two leptons or hadrons. The requirement that the signal region has an invariant mass of the displaced vertex
(\(m_{DV}\)) larger than 4 GeV, and the good mass resolution seen in the \(J/\Psi\) and \(\Psi(2S)\) resonances shows that no contamination from the low-mass region is expected. The distributions of \(m_{DV}\) and radial distances \(r_{DV}\) are compared between opposite sign and same sign vertices which pass baseline selections in Fig. 7.1, 7.2 and 7.3. Agreements are seen between opposite sign and same sign, and guarantee our assumption for the data-driven background estimation.

![Figure 7.1: The distributions of reconstructed masses (\(m_{DV}\), left) and radial distances (\(r_{DV}\), right) for non-lepton tracks DVs. The distributions for opposite sign DVs and same sign DVs are compared. For \(r_{DV}\) distribution, \(m_{DV}\) is required more than 4 GeV.](image)

![Figure 7.2: The distributions of reconstructed masses (\(m_{DV}\), left) and radial distances (\(r_{DV}\), right) for one-muon + non-lepton track DVs requiring a loose lepton in each of them to get more statistics. The distributions for opposite sign DVs and same sign DVs are compared. For \(r_{DV}\) distribution, \(m_{DV}\) is required more than 4 GeV.](image)

## 7.2 Validation of Method

To validate our data-driven background estimation method, one-lepton validation regions (A’ and C’) are used. As an analogy of the background estimation in the signal region, the number of events
Figure 7.3: The distributions of reconstructed masses ($m_{DV}$, left) and radial distances ($r_{DV}$, right) for one-electron + non-lepton track DVs requiring loose lepton in each of them to get more statistics. The distributions for opposite sign DVs and same sign DVs are compared. For $r_{DV}$ distribution, $m_{DV}$ is required more than 4 GeV.

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight $\mu$</td>
<td>49 ± 7</td>
<td>54</td>
</tr>
<tr>
<td>Tight $e$</td>
<td>19 ± 4</td>
<td>23</td>
</tr>
<tr>
<td>Medium $\mu$</td>
<td>178 ± 13</td>
<td>210</td>
</tr>
<tr>
<td>Medium $e$</td>
<td>19 ± 4</td>
<td>16</td>
</tr>
<tr>
<td>Loose $\mu$</td>
<td>718 ± 27</td>
<td>739</td>
</tr>
<tr>
<td>Loose $e$</td>
<td>24 ± 5</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 7.2: The validation of the data-driven method in 12 statistically independent regions for the low density region (left) and high density region (right).

in region A’ is estimated by $BC'/D$. This estimation is performed for one muon + one non-lepton track DVs and one electron + one non-lepton track DVs respectively. The numbers of expected events and observed events are compared as a function of the invariant mass of a displaced vertex (Fig. 7.4). The number of events expected in region A’ is 89 and the prediction is 82 ± 9 for one-muon DVs. For one-electron DVs, the number of expected events is 35 and of predicted events is 28 ± 5. The validation is also performed in 12 statistically independent regions, changing lepton quality and divided in low density region and high density region (i.e. DVs satisfying tight criteria are not included in medium category). The results are summarized in Table. 7.2.

### 7.3 Background Estimation

In the signal region (A), our study convincingly shows that background occurrences do not depend on the material density nor on the sign configuration of the tracks inside the DVs.

The estimated number of background events in the signal region is 0 event with an uncertainty of < 2.3 events at 90% confidence level.
7.3. BACKGROUND ESTIMATION

Figure 7.4: Validation of the background estimation as a function of a displaced vertex invariant mass ($m_{DV}$) for one muon (top) and for one electron (bottom) validation regions.
Chapter 8

Systematic Uncertainties

In this analysis, there are various types of systematic uncertainties. Each of them is discussed in this chapter.

8.1 Trigger and Prompt Muon Reconstruction

The prompt muon is used in triggering and a part of the DRAW filter. Possible factors which may affect the selection efficiency estimated from our MC simulation include uncertainties related to the trigger, reconstruction, identification, isolation, energy scale, pile-up modelling, and PDF. We use well-documented studies in ATLAS to evaluate these systematics which yield a 1% systematic uncertainty. Since it is very small compared to the other systematics, we double it and use a conservative 2% systematic uncertainty.

8.2 Displaced Track Reconstruction

The uncertainty in the MC modelling of the track reconstruction efficiency for large-\(d_0\) tracks is studied using a large data sample of \(K_S^0\) decays into two pions. The \(\Sigma p_T\) distributions of data and MC are separately obtained for various regions of \(r_{DV}\) to compare their respective efficiencies. Based on these results, \(r_{DV}\) and \(\Sigma p_T\)-dependent weights are obtained and applied to vertices in the signal region to estimate variations in the signal efficiency due to uncertainties in the track and the vertex reconstruction efficiencies. This results in an at most 15% relative uncertainty in the selection efficiency, which is used as a conservative estimate for all points. The details of this estimation is described in the following subsections.

8.2.1 Method

The assumption is that the tracking is already well understood for tracks close to the primary vertices (PVs) as all of ATLAS analyses uses such tracks and our aim here is to see the variation of the efficiency with the increase of the radial distances of the vertices. For this purpose, the \(K_S^0\) mesons are used as we expect enough statistics of them coming from pile-up events and have a considerably long lifetime resulting in the decay distance of about 27 mm. Apart from these, the charged pions (\(\pi^+, \pi^-\)) are abundant in ATLAS, which will facilitate the \(K_S^0\) reconstruction. Therefore, \(K_S^0\) mesons can be used to find out the ratio between data and MC for the efficiency of
tracking for tracks that emerge from a vertex at $r_{DV}$. The ultimate goal is to obtain the correction factors for displaced track efficiencies.

### 8.2.2 $K^0_S$ reconstruction

The decay channels $K^0_S \rightarrow \pi^+\pi^-$, has a large branching ratio ($\sim 69\%$) as compared to other channels. The $K^0_S$'s are reconstructed with the $\pi^+$ and $\pi^-$ tracks originating from displaced vertices. A mass cut of $K^0_S$ mass $\pm 10$ MeV is applied on the reconstructed displaced vertex mass ($m_{DV}$), i.e. $487$ MeV $< m_{DV} < 507$ MeV is used. The distributions of $m_{DV}$ for real data and MC samples are shown in Fig. 8.1. Further, we apply a cut of $< 0.01$ radian on $\alpha$ which is the angle between the direction of $r_{DV}$ (the direction from the most energetic PV to the $K^0_S$ vertex) and the reconstructed $K^0_S$ momentum. This angle, $\alpha$, is only in the transverse plane, hence not 3-dimensional.

![Figure 8.1: The invariant mass distribution of reconstructed $K^0_S$ candidates for data and MC.](image)

### 8.2.3 Data-MC correction using $K^0_S$

As shown in Fig. 8.2 (left), the scalar sum of the transverse momenta of $K^0_S$ tracks ($\Sigma p_T = p_T^{\pi^+} + p_T^{\pi^-}$) is not identical in data and MC. Therefore, the efficiency might depend on $\Sigma p_T$ as well as $r_{DV}$ (Fig. 8.2 right). The method to obtain the data-MC correction using $K^0_S$ can be split into following steps:
Figure 8.2: The distributions of sum of the transverse momenta of $K_0^S$ tracks ($\Sigma p_T = p_T^{π^+} + p_T^{π^-}$) (left) and the distribution of reconstructed radial position of $K_0^S$ vertices for the data and the MC.

<table>
<thead>
<tr>
<th>$\Sigma p_T$ bin</th>
<th>Range [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000–2500</td>
</tr>
<tr>
<td>2</td>
<td>2500–3000</td>
</tr>
<tr>
<td>3</td>
<td>3000–4000</td>
</tr>
<tr>
<td>4</td>
<td>4000–6000</td>
</tr>
<tr>
<td>5</td>
<td>6000–8000</td>
</tr>
<tr>
<td>6</td>
<td>8000–10000</td>
</tr>
<tr>
<td>7</td>
<td>&gt; 10000</td>
</tr>
</tbody>
</table>

Table 8.1: Definition of $\Sigma p_T$ bins and their ranges.
1. The bins of $\Sigma p_T$ are chosen depending on their ranges (Table. 8.1).

2. A number of $r_{DV}$ bins are also defined. The total number of $r_{DV}$ bins is 15. Each bin has a uniform width of 20 mm except for the last bin, which is 16 mm wide. The $r_{DV}$ region covered in total is 4–300 mm.

3. For each $\Sigma p_T$ bin, the observed $r_{DV}$ distribution histogram is plotted for both data and MC, denoted as $H_{r_{DV}}^{data}$ and $H_{r_{DV}}^{MC}$, respectively.

4. The corresponding “expected” exponential is determined separately for data and MC:
   \[ e(r_{DV}) = \exp \left( -\frac{r_{DV} m}{p_T c_T} \right). \] (8.1)

   For the estimation of $e(r_{DV})$, average $p_T$ values within corresponding $\Sigma p_T$ bins are used. $r_{DV}$ remains the only variable (all other quantities have fixed values).

   In principle, $e(r_{DV})$ is determined by integrating over the $p_T$ values and taking the linear approximation. For a given $r_{DV}$ bin, $e_{data}^{r_{DV}}$ and $e_{MC}^{r_{DV}}$ are close to each other; where $e_{data}^{r_{DV}}$ and $e_{MC}^{r_{DV}}$ correspond to the expected exponentials for data and MC respectively.

5. The $r_{DV}$-dependent efficiency distribution ($\epsilon$) is plotted for each $\Sigma p_T$ bin:
   \[ \epsilon_{r_{DV}}^{data} = \frac{H_{r_{DV}}^{data}}{e_{data}^{r_{DV}}}, \] (8.2)
   \[ \epsilon_{r_{DV}}^{MC} = \frac{H_{r_{DV}}^{MC}}{e_{MC}^{r_{DV}}}. \] (8.3)

6. Then, the unnormalized efficiency ratio ($w(r_{DV})$) is plotted as per the following relation:
   \[ w(r_{DV}) = \frac{\epsilon_{r_{DV}}^{data}}{\epsilon_{r_{DV}}^{MC}}. \] (8.4)

7. Normalization of $w(r_{DV})$. $w(r_{DV})$ is normalized so that it equals to 1 in the innermost region of $r_{DV}$. We choose to normalize $w(r_{DV})$ in this way, because the innermost region is the nearest region to the interaction point, and hence the most robust one. The resulting $w(r_{DV})$ is plotted. This is nominally the “correction”. A few points regarding the normalization procedure are:
   - If the innermost $r_{DV}$ region is empty for the high-$\Sigma p_T$ bins, those high-$\Sigma p_T$ bins are normalized in a region close to the interaction point which has a nonzero value.
   - $w(r_{DV})$ is normalized/scaled with a factor of $1.0 / \left( \left| \frac{D(i)}{M(i)} \right| \right)$ or $1.0 / \left( \left| \frac{D(i)+D(j)}{M(i)+M(j)} \right| \right)$ depending on the statistics of the bins concerned (if the statistics are low, we go for the second normalization factor) and the corresponding error on it is calculated. $D(i)$ ($M(i)$) and $D(j)$ ($M(j)$) denotes the number of events in the lowest first ($i$) and second ($j$) nonzero bins for data (MC). If the number of events in a particular $r_{DV}$ range is used for normalization, then the number of events in that range should be used for the error calculation as well.
   - Statistical error for each bin is propagated to the normalized-$w(r_{DV})$. 
8.2.4 Results

The correction factors are applied on an event-by-event basis, and the vertex reconstruction efficiencies are calculated for HNL MC samples ($c\tau = 10$ mm) using the obtained normalized-$w$ values. There are some bins with no correction factor (i.e. the empty bins), and for such bins $w(r_{DV}) = 1$ is applied (about 30% for $m_{HNL} = 5$ GeV $c\tau = 10$ mm sample). Finally, a systematic uncertainty of 15% is estimated as the maximum difference between HNL vertex reconstruction efficiencies obtained with and without weights.

<table>
<thead>
<tr>
<th>HNL mass</th>
<th># of events without weight</th>
<th># of events with weight</th>
<th>reconstruction efficiency with weight</th>
<th>reconstruction efficiency without weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 GeV</td>
<td>306 ± 17</td>
<td>270 ± 36</td>
<td>0.0031</td>
<td>0.0027</td>
</tr>
<tr>
<td>7.5 GeV</td>
<td>682 ± 26</td>
<td>623 ± 75</td>
<td>0.015</td>
<td>0.013</td>
</tr>
<tr>
<td>10 GeV</td>
<td>2025 ± 45</td>
<td>1898 ± 178</td>
<td>0.025</td>
<td>0.024</td>
</tr>
<tr>
<td>12.5 GeV</td>
<td>1109 ± 33</td>
<td>1064 ± 82</td>
<td>0.022</td>
<td>0.021</td>
</tr>
</tbody>
</table>

Table 8.2: The number of reconstructed events and reconstruction efficiencies before and after applying correction factors.

8.3 Displaced Lepton Identification

For particles emerging from the DV, the lepton ID efficiency assuming the track is reconstructed is much higher than the DV reconstruction efficiency. It is reasonable to assume that the latter largely dominates the uncertainty and that effects due to MC modelling of the lepton identification can account for a few % for prompt leptons. Also, such effects are very difficult to study as it is notoriously difficult to find clean samples of displaced leptons. We assume a conservative 5% systematic uncertainty from this contribution.

8.4 Initial State Radiation

In the MC used in this analysis, the initial state radiation (ISR) of gluons and photons is added by PYTHIA8 at the event generation stage. PYTHIA8 may however not be perfectly accurate with modelling ISR. In the present case, ISR may occasionally introduce a transverse boost of the $W$ boson and thus increase the $p_T$ of the leptons from the $W$ and HNL decays, and this can affect the trigger efficiency and the filter efficiency, both of which apply $p_T$ thresholds. To estimate the systematic uncertainty related to the ISR modelling, ISR is implemented using both the PYTHIA8 and Powheg+PYTHIA8 (in this case Powheg being used for ISR and PYTHIA8 being used only for the hadronization) generators, and then the final selection efficiencies are compared. The difference in the final efficiency between the different models is found to be less than 1% and thus we neglect this contribution.
8.5 HNL Decay Modeling

In our signal samples, HNL decays are modelled in PYTHIA8 using a simple three-body decay to two charged leptons and a neutrino. This is an approximation as the HNLs in fact should decay to a charged lepton and a virtual $W$ boson which in turn decays into another charged lepton and a neutrino. For HNL masses, much lower than the $W$ mass, as in this search, this approximation is expected to be rather accurate.

To estimate the systematic uncertainty related to this approximation, a sample is generated using a PYTHIA8 model which correctly describes the HNL decay. It explicitly requires the presence of a virtual $W$ boson in the decay. The difference in the final efficiency between the two models is used as a systematic uncertainty. Comparison were made with three produced samples, for an HNL of a mass of 10 GeV, for three different lifetimes: 1, 10 and 100 mm. For the 1 and 10 mm the efficiency differences are very small and inside the statistical uncertainties, and for 100 mm it is a bit superior to the statistical uncertainties: difference in efficiencies is 10%. This large uncertainty of 10\% is mainly due to the limited statistics of the sample dedicated to this systematic study. To be conservative we take this value and extend it to all other samples.

8.6 HNL Decay Branching Ratio

In this analysis, the case where the HNL violates lepton number (LNV) and conserve lepton number (LNC) are considered and the branching ratios are different between them. For LNV, the branching ratio is 0.166 as mentioned in Sec. 4.1. For LNC, the branching ratio for HNL decays to $l^+l^-\nu$ in the HNL mass range 3–20 GeV is computed to be 0.27 by taking into account all partial decay widths. In an article which also performs such a calculation, it is reported to be $0.25 \pm 0.02$ [29]. Thus a 7\% systematic uncertainty is added due to the uncertainty in the branching ratio.

8.7 Uncertainty on $W$ Production Cross Section

A signal strength scales with the $W$ production cross section for $W$ decays to a signal lepton flavour (here muons). This cross section is obtained from a direct ATLAS measurement in 13 TeV $pp$ collisions which quotes a 3\% uncertainty [68], also taken as a systematic uncertainty for our results.

8.8 Integrated Luminosity

The uncertainty in the 2016 integrated luminosity is 2.1\%. It is derived following a metrology from a calibration of the luminosity scale using $x$-$y$ beam separation scans performed in August 2015 and May 2016 [69].

8.9 Pile-up

The uncertainty related to the pile-up events from the collision conditions is computed using the Pileup Reweighting tool designed for the Exotics Physics analyses. The configuration files are selected for each MC sample, and linked to the luminosity calculation files, using the data taking
conditions of 2016 in ATLAS. We collect the systematic uncertainty for each mass and lifetime point sample, due specifically to pileup reweighting process. The results are gathered in Table 8.3. The uncertainty is of the order of 10%.

<table>
<thead>
<tr>
<th>lifetime vs masses</th>
<th>5 GeV</th>
<th>7.5 GeV</th>
<th>10 GeV</th>
<th>12.5 GeV</th>
<th>15 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>40%</td>
<td>1.5%</td>
<td>6.7%</td>
<td>7.7%</td>
<td>15.5%</td>
</tr>
<tr>
<td>10 mm</td>
<td>5.9%</td>
<td>7.5%</td>
<td>3.6%</td>
<td>3.5%</td>
<td>8.3%</td>
</tr>
<tr>
<td>100 mm</td>
<td>12.8%</td>
<td>11%</td>
<td>3.2%</td>
<td>6.7%</td>
<td>7.4%</td>
</tr>
</tbody>
</table>

Table 8.3: Systematic uncertainties due to pileup reweighting of the samples.

### 8.10 Uncertainty due to MC Statistics

Limited MC statistics result in a 10% uncertainty for most signal masses and lifetimes which have a selection efficiency around 1%. The uncertainty can be larger in the case of $c\tau = 1$ mm, for which the search is not sensitive because the efficiency is too low.

### 8.11 Total Systematic Uncertainty

The various contributions to the systematic uncertainty in signal yield are summarized in Table 8.4. Adding them in quadrature gives a total systematic uncertainty of 24%.

<table>
<thead>
<tr>
<th>Source of systematics</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt muon reconstruction and trigger</td>
<td>1</td>
</tr>
<tr>
<td>Displaced track reconstruction</td>
<td>15</td>
</tr>
<tr>
<td>Displaced lepton identification</td>
<td>5</td>
</tr>
<tr>
<td>Initial-state radiation</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>HNL decay modelling</td>
<td>10</td>
</tr>
<tr>
<td>HNL decay branching ratio</td>
<td>7</td>
</tr>
<tr>
<td>$W$ production cross section</td>
<td>3</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.1</td>
</tr>
<tr>
<td>Pileup modelling</td>
<td>10</td>
</tr>
<tr>
<td>MC statistics</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24</strong></td>
</tr>
</tbody>
</table>

Table 8.4: Summary of systematic uncertainties.
Chapter 9

Results and Interpretation

9.1 Results

The signal region is unblinded after background estimation. No events are observed in our signal region. The distributions of reconstructed vertex masses ($m_{DV}$) and radial distances ($r_{DV}$) after all event selections except for the mass cut are plotted together with those of signal MC samples in Fig. 9.1.

![Figure 9.1](image_url)

Figure 9.1: Reconstructed vertex mass $m_{DV}$ (left) and radial distance $r_{DV}$ (right) distributions in data and signal MC samples after requiring all event selection criteria except for the mass cut. MC distributions are normalized to the expected number of events using the luminosity, cross sections, and efficiencies.

9.2 Lifetime Reweighting

To make limit plots, the selection efficiencies are calculated for intermediate lifetime points which are not available using the fully simulated samples. The procedure is as follows:

- The selection efficiencies are plotted as a function of the actual decay length ($c\tau$) with simulated samples for each mass merging different mass samples (Fig. 9.2).
The distribution of the decay length for the particle with the lifetime $\tau$ should be proportional to $\exp\left(-\frac{x}{c\tau}\right)$. Therefore, multiplying the selection efficiencies to this distribution results in the selection efficiencies distribution after appropriate normalization.

Integrating the distribution to obtain the total selection efficiency for the corresponding mean decay length.

```
\begin{figure}
\centering
\includegraphics[width=\textwidth]{selection_efficiency}
\caption{The signal selection efficiencies are plotted as a function of the actual decay length for 5 GeV HNL mass samples. The different lifetime samples are merged and the broad range efficiencies with respect to decay length are obtained.}
\end{figure}
```

Figure 9.2: The signal selection efficiencies are plotted as a function of the actual decay length for 5 GeV HNL mass samples. The different lifetime samples are merged and the broad range efficiencies with respect to decay length are obtained.

In Fig. 9.3, the obtained efficiencies are shown.

### 9.3 Exclusion Limits

The total $W$ boson production cross section in 13 TeV $pp$ collisions for decaying into a muon is obtained from the ATLAS measurement as $(2.06 \pm 0.06) \cdot 10^7$ fb. The branching ratio for the $W$ decay to HNL is obtained from Eq. (4.2), with $m_W = 80.4$ GeV. The value of $U^2$ used in this calculation is obtained from the value of the generated signal lifetime using Eq. (4.3). The branching ratio for the HNL decay into $\mu + e + \nu_e$ or $\mu + \mu + \nu_\mu$ is taken to be 0.166 with 7% relative uncertainty.
9.3. EXCLUSION LIMITS

Figure 9.3: Selection efficiency as a function of the mean $c\tau$ obtained by folding the efficiency as a function of the actual $c\tau$ with the corresponding exponential probability distribution function. Efficiencies obtained from the fully simulated sample for $c\tau = 1, 10, 100$ mm are also shown as red stars.

Histfitter [70] is used to compute the p-value (probability, if there is a signal, to obtain the observed number of events after selection, assuming the background-only hypothesis) for the different HNL masses and lifetimes. The calculation is performed in the frequentist profile likelihood test statistic using a smart toy. The framework is used to compute the observed limit and can compute the expected limit as well if needed (which takes longer because it needs to throw more toys to compute the average limit). For a given mass and lifetime, the inputs to these calculations are as follows.

- The selection efficiency.
- Uncertainties in the selection efficiency.
- The signal cross section times branching ratio.
- The number of observed events for the observed limit calculations.
- The number of expected backgrounds with uncertainties for the expected limit calculations. Our background estimate is 0 events with an uncertainty of 2.3 events.
- The integrated luminosity with uncertainties ($32.9 \pm 1.0$ fb$^{-1}$).
The p-values are then used to generate 95% C.L. contour exclusion plots in the $U^2$ versus mass plane corresponding to $p < 0.05$. The expected limits and the observed exclusion contour, with zero observed events in the signal region, are shown in Fig. 9.1. A more elaborate way to compute the limit is to use four bins corresponding to the A, B, C, and D regions used in the background estimate. The observed limit in the case of zero observed event in A is identical to the simple limit, as expected.

The limit contour takes the shape of an oblique band which roughly corresponds to HNL lifetimes within our fiducial volume of 4 – 300 mm displacement (Fig. 9.4). It is also limited from below by the product of integrated luminosity and efficiency, limiting the reach to $U^2 \sim 10^{-6}$ for the current search. The interpretation with LNV provides weaker limits because the search is sensitive to long lifetimes and, for the same coupling, the lifetime is reduced by a factor of two rather than LNC when LNV decays are opened. We show both interpretations to clarify this model dependence.

Our search probes new territory at a small coupling in the HNL mass range 5–9 GeV. A stronger limit than the previous limit set by DELPHI experiment at LEP1 is obtained. This reach will be improved in future searches as it depends linearly on the integrated luminosity as long as the search remains background-free.
Figure 9.4: Observed 95% C.L. exclusion (red lines) in the coupling ($U^2$, for dominant HNL mixing with $\nu_\mu$) versus HNL mass plane, for the LNV (top) and LNC (bottom) interpretations. Expected limits at 1$\sigma$ and 2$\sigma$ are shown as green and yellow bands.
Chapter 10

Conclusion

We perform a search for the signature of a prompt muon accompanied with a displaced vertex consisting of two opposite-sign leptons (either two muons or a muon and an electron) with a reconstructed vertex mass above 4 GeV, using 32.9 fb$^{-1}$ of 13 TeV $pp$ collision data collected from the ATLAS detector in 2016. Backgrounds from decays of the SM particles and cosmic ray muons are studied in detail and rejected completely from our signal region. The remaining backgrounds from randomly crossing tracks are estimated by a data-driven method. Displaced vertices containing low-$p_T$ tracks with a reconstructed vertex mass below 10 GeV are probed for the first time at the LHC. We observe no events in our signal region, consistent with a data-driven background expectation of $< 2.3$ events. We interpret these results in a simple model of type-I seesaw heavy neutral leptons (HNLs) mixing with $\nu_\mu$ produced in $W$ boson decays. New limits are obtained on this mixing in the HNL mass range 5–9 GeV, surpassing the previous limits set by the DELPHI experiment at LEP1.
Bibliography


