

SEARCH FOR LONG-LIVED RESONANCE
DECAYING TO A DILEPTON PAIR IN pp
COLLISIONS AT $\sqrt{s} = 13$ TEV WITH
THE ATLAS DETECTOR

DISSERTATION

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ABSTRACT

A search for long-lived neutral massive particle decaying to a $\mu\mu$, ee , or $e\mu$ pair is presented using the ATLAS detector with 32.8 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ at the LHC. Upper limits are presented on the production cross section times branching ratio for resonances decaying to a lepton pair. Also presented is the detection efficiency as a function of p_T and η for a resonance with mass of $0.1\text{--}2.0 \text{ TeV}$ and lifetime ($c\tau$) of $100\text{--}500 \text{ mm}$.

Dedication

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I would like to thank my parents for their endless support and love. Also, I would like to thank Prof. K.K. Gan for his guidance and support throughout my graduate career. Add more text.

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Chapter 1

INTRODUCTION AND THEORY

In this chapter, the theoretical background and motivation for the search for new physics with long-lived particles are presented. In Section 1.1, an overview of the Standard Model of particle physics is presented. In Section 1.2 the theories beyond the Standard Model that predict new long-lived gauge bosons and the potential discovery mode of the new particles are discussed.

1.1 The Standard Model

The Standard Model (SM) [2] of particle physics has been a very successful theory in modern physics that describes the known fundamental particles and their interactions. The SM is a gauge theory based on $SU(3) \otimes SU(2) \otimes U(1)$ symmetry group. The symmetry group describes three fundamental interactions, quantum chromodynamics (QCD), quantum electrodynamics (QED), and weak interactions, which arises from the requirement of local gauge invariance. The much weaker gravity is not incorporated in the SM. All known matters are described by spin $\frac{1}{2}$ fermions, and the interactions between the fermions are mediated by spin 1 gauge bosons. Fermions acquire mass by interacting with the Higgs field H via spontaneous symmetry breaking [3].

1.1.1 Fundamental Particles and Interactions

The elementary particles in the SM can be divided into two groups, fermions and bosons, and all elementary particles have associated anti-particles with the same property but with opposite charge.

Fermions are spin $\frac{1}{2}$ particles that constitute the building blocks of matter, and they can be divided into two groups, leptons and quarks. Leptons are colorless particles that do not interact through the strong force, and quarks are subject to the strong force due to color charges. There are three generations of leptons and quarks in increasing mass, and each generation consists of two leptons (electric charge 1 or 0) and two quarks (electric charge $\frac{2}{3}$ or $-\frac{1}{3}$). Quarks and charged leptons interact through the electroweak interaction while neutrinos only experience weak interaction. Fermions are described as quantum fields with *left-handed* or *right-handed* chirality, and only *left-handed* fermions and *right-handed* antifermions are subject to the weak interaction. This phenomenon is known as CP-violation [4]. Quarks are not observed as free particles due to *color confinement* [5], but they are only observed in color-neutral bound states, called *hadrons*. There are two types of hadrons: *mesons* and *baryons*. Mesons are composite particles with quark and anti-quark pair, and baryons are composed of three quarks. The elementary fermions are summarized in Table 1.1.

	Generation			Q	Mass (MeV)	
	1 st	2 nd	3 rd			
Leptons	ν_e	ν_μ	ν_τ	0	0	0
	e	μ	τ	-1	0.511	105.7
Quarks	u	c	t	+2/3	2.3	1275
	d	s	b	-1/3	4.8	95
						173070
						4180

Table 1.1: The fundamental fermions and their electric charge Q and masses.

The fundamental interactions are described by gauge bosons, spin 1 particles that are generated by the symmetry groups in the SM. Gluon fields are generated by $SU(3)$ group, and quanta of gluon fields produce massless gluons that mediate strong forces. The group $SU(2) \otimes U(1)$ generates gauge fields W_μ^a ($a = 1, 2, 3$) and B_μ which mediate electroweak force. The physical observable gauge bosons W^\pm , Z , and photon are created by the mixing of these gauge fields,

$$\begin{aligned} W_\mu^\pm &= (W_\mu^1 \mp iW_\mu^2)/\sqrt{2} \\ Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \end{aligned} \tag{1.1}$$

where θ_W is the weak mixing angle.

Photon and gluons are massless, and W^\pm and Z bosons gain masses through the Higgs

mechanism [6] via spontaneous symmetry breaking. In the Higgs mechanism, an additional complex scalar field, called Higgs field, is introduced with $SU(2)$ symmetry, and because the Higgs potential has non trivial vacuum expectation value, the symmetry of the ground state is spontaneously broken, leading to a massive scalar particle with spin 0, known as Higgs boson. The gauge bosons and their associated fields, and masses are summarized in Table 1.2

Symmetry	Gauge boson	Gauge Field	Q	Mass (GeV)
$SU(2) \otimes U(1)$	γ	A_μ	0	0
	Z	Z_μ	0	91.2
	W^\pm	W_μ^\pm	± 1	80.4
$SU(3)$	g	g_μ^a	0	0

Table 1.2: Gauge bosons and their associated fields and masses.

1.2 Beyond the Standard Model

Although the SM has been the most successful theory at explaining fundamental particles and their interactions, there are several experimental observations and phenomena in nature that are not fully explained by the SM. These phenomena include gravity [7], hierarchy problem [8] [9], dark matter [10] [11] [12], neutrino oscillations [13] [14], and matter-antimatter asymmetry [15] [16].

Many Beyond the Standard Model (BSM) theories that predict the existence of new particles have been proposed to explain these unexplained phenomena. In particular, theories such as Hidden Valley [17] [18], R-parity violation [19] [20], and Z' models with neutrinos [21] predict the existence of weakly-coupled, neutral gauge boson at the weak scale. The new gauge boson is called Z' due to the similarity to the standard Z boson.

1.2.1 Z' from the extension of the Standard Model

The new weakly-coupled gauge boson can be added to the SM by including a additional $U(1)'$ symmetry to the existing $SU(3) \otimes SU(2) \otimes U(1)$ symmetry. The spontaneous breaking of the $U(1)'$ symmetry, similar to the electroweak symmetry breaking, produces the new gauge boson, Z' [22]. The mechanism through which the new symmetry is added to the SM varies by theories. Nonetheless, the Z' boson has two sets of parameters defining its property: the couplings to the SM particles and the energy scale at which the $U(1)'$ symmetry is broken.

The former defines the lifetime, $c\tau$, of the particle while the latter defines the mass of the particle.

In one case, Z' can have the same couplings to fermions as the SM Z boson, and the particle is called *sequential* Z' [23]. There have been several searches for the sequential Z' [24] [25] [26], and although the sequential Z' provides useful reference for some theories, it will not be considered in this thesis as the main focus of the analysis is the long-lived particles.

In other case, the Z' can have very small couplings to the SM particles such that the particle have a finite lifetime compatible with the detector volume at the ATLAS experiment. This metastable particle is called the *long-lived* Z' , and this model will be used as a basis of this thesis.

1.2.2 Long-lived Z' Discovery Mode at the LHC

The long-lived Z' can be directly produced and discovered from pp collisions at the Large Hadron Collider (LHC). The primary discovery mode for the long-lived Z' is via the Drell-Yan (DY) production of a dilepton resonance, $pp \rightarrow Z' \rightarrow \ell^+\ell^-$ where $\ell = e$ or μ [27].

The cross section for Z' decaying to two leptons ($pp \rightarrow Z' \rightarrow \ell\bar{\ell}$) is simply given by Eq. 1.2 [28],

$$\sigma_{Z'}^\ell = \sigma_{Z'} B_\ell = \frac{N_\ell}{\mathcal{L}_I} \quad (1.2)$$

where $\sigma_{Z'}$ is the production cross section of Z' , $B_\ell = \Gamma_f/\Gamma_{Z'}$ is the branching ratio of Z' into $\ell\bar{\ell}$, and N_ℓ is the number of $\ell\bar{\ell}$ produced for integrated luminosity \mathcal{L}_I . Therefore, if Z' is light enough to be produced at the LHC, the sensitivity to detect Z' depends on luminosity, the production cross section, and the branching ratio into a particular channel.

Long-lived particles naturally have small width ($\tau_0 = \hbar/\Gamma$), and the detectable mass range and lifetime of Z' is constrained by the center of mass energy (13 TeV in Run II) and the detector volume ($\sim O(1m)$).

Other potential discovery channels exist in searches for Z' such as $Z' \rightarrow \tau^+\tau^-$ and hadronic decay, $Z' \rightarrow jj$ where $j = \text{jet}$ although these decay modes are more experimentally difficult to detect due to the irreducible QCD background. But the search for long-lived Z' through a dilepton resonance is particularly interesting due to its clean final signature and low backgrounds from the SM.

More rare decays are also possible such as $Z' \rightarrow V f_1 \bar{f}_2$ where $V = W, Z$ or Z' decaying to two bosons, but these rare decays will be extremely difficult to detect due to the small branching ratio [28].

Chapter 2

THE ATLAS EXPERIMENT AT THE LHC

The ATLAS experiment is one of the four major experiments at the LHC at the European Organization for Nuclear Research (CERN). The ATLAS detector is designed as a general-purpose particle experiment, together with the CMS experiment. In Section 2.1, a brief description of the LHC is given, and in Section 2.2, the ATLAS detector and its sub-detector systems are described.

2.1 The Large Hadron Collider

The LHC is the world’s largest synchrotron accelerator (pp collider) located at CERN near Geneva, Switzerland. The LHC’s circular beam pipes are 27 km in circumference, and two beams of protons are accelerated in opposite direction producing pp collisions at $\sqrt{s} = 13$ TeV in Run II. Separate magnet systems are used to direct proton beams in each direction.

There are 8 interaction regions (IRs) at which two proton beams cross, and protons beams are injected into the LHC from two IRs. Before protons are injected to the LHC, they undergo a multi-stage acceleration by several accelerators [29]: a linear accelerator (LINAC2), the Proton Synchrotron Booster, the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS). The proton beams are accelerated up to 450 GeV when they are injected to the LHC with a 25 ns bunch spacing in Run II. There are more than 10^{11} protons in each bunch, and the large number of protons in each bunch results in multiple collisions per bunch crossing, knowns as *pile-up*. In 2016, the mean number of interactions per bunch crossing was $\langle \mu \rangle = 24.9$.

The four main experiments at CERN are distributed around the LHC at collision points. Two experiments, ATLAS and CMS, are designed as general purpose experiments, and A

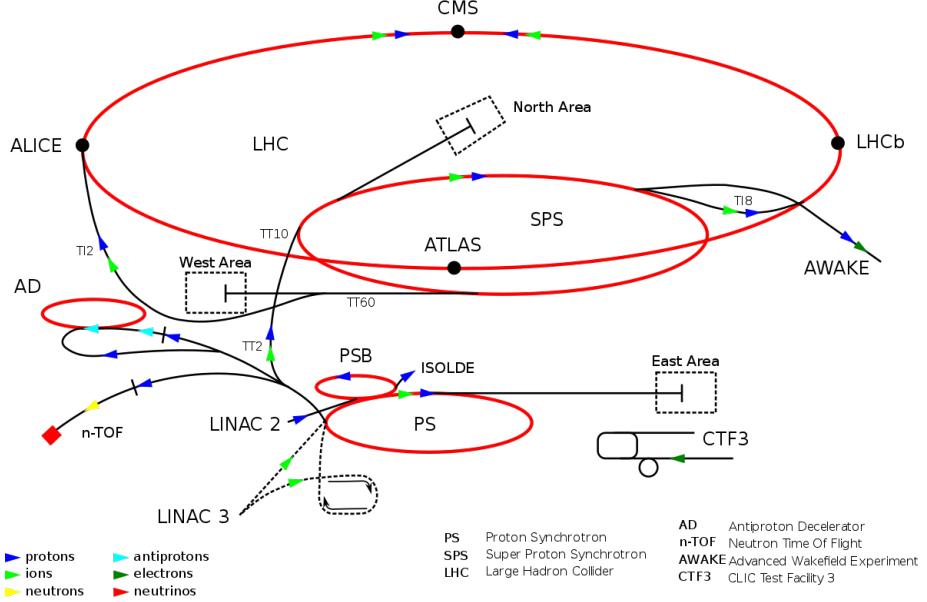


Figure 2.1: An illustration of the LHC accelerators and the four main experiments.

large Ion Collider Experiment (ALICE) and the Large Hadron Collider beauty (LHCb) are designed to study strong interaction using heavy ion collisions and the matter-antimatter asymmetry using b quarks, respectively. Figure 2.1 shows the four main experiments and the accelerators at the LHC.

2.2 The ATLAS detector

The ATLAS detector is a multi-purpose detector designed to investigate a wide range of physics, including the search for the Higgs boson in Run I and many searches beyond the SM. The detector measures 46 m long, 25 m in diameter, and it has three main layers of sub-detectors to detect particles created from pp collisions at the Interaction Point (IP). Figure 2.2 shows the ATLAS detector and the sub-detector systems: the Inner detector, the electromagnetic and hadronic calorimeters, and the muon spectrometer. In this section, the coordinate system, the sub-detectors, and the magnet system of the ATLAS detector are described.

2.2.1 Coordinate System

In the ATLAS coordinate system, the interaction point (IP) is defined as the origin of the coordinate system. The beam line defines the z-axis, and the x-y plane perpendicular to the

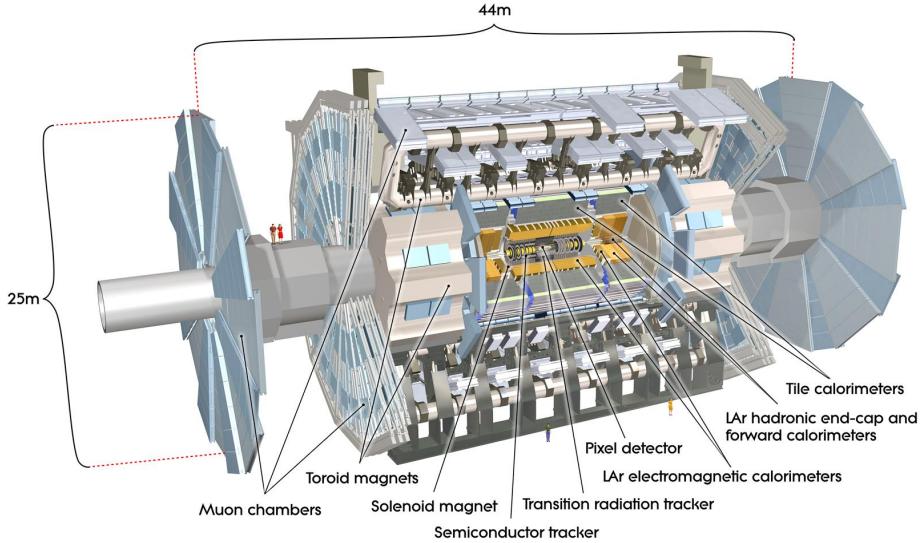


Figure 2.2: The ATLAS detector showing three sub-detector systems.

beam line is referred to as the transverse plane. The positive x-axis points from the IP to the center of the LHC ring, and the positive y-axis is defined as pointing upward. The azimuthal angle ϕ is defined as the angle from the x-axis. The polar angle θ is defined as the angle from the positive z-axis, and it is also expressed as pseudo-rapidity η ,

$$\eta = -\ln(\tan(\frac{\theta}{2})), \quad (2.1)$$

which is a particularly useful quantity because of Lorentz invariance under a boost along the z axis. The distance ΔR is defined in $\eta - \phi$ plane as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

2.2.2 The Inner Detector

The Inner Detector (ID) is a particle tracker designed to measure the charge and transverse momentum of charged particles and to reconstruct the primary and secondary vertices. It consists of cylindrical barrels and two end-cap disks from three sub-detectors centered around the IP. The ID covers the pseudo-rapidity region up to $|\eta| < 2.5$.

The detector is immersed in a 2 T magnetic field generated by the superconducting solenoid magnets, and the magnetic field is used to bend trajectories of charged particles. The transverse momentum and the charge of a particles are then determined from the curvature of the trajectory.

The sub-detectors of the ID, the Pixel tracker, the semiconductor tracker (SCT), and the transition radiation tracker (TRT), are discussed in the following sections.

Pixel Detector

The Pixel detector is a semiconductor detector in the innermost part of the ATLAS tracking system. The detector consists of 4 concentric layers of barrel detectors and 3 disk detectors at each end-cap region. The barrels and disks are made of a rectangular Pixel modules containing $80.4 \cdot 10^6$ pixels of the size $50 \times 400 \mu\text{m}^2$ ($6 \cdot 10^6$ pixels of the size $50 \times 250 \mu\text{m}^2$ for the IBL) [30]. As a charged particle traverse through pixels, the currents generated by ionizing electrons are measured and registered as hits. The pixels provide spatial information with resolution of $\sim 8 \mu\text{m}$ in radial direction and $\sim 75 \mu\text{m}$ in the beam axis, and the information is used for momentum measurements as well as reconstruction of primary and secondary vertices. In Run 2, the Insertable B-Layer (IBL) [31] was installed to maintain and improve the performance of the ATLAS detector under increasing pile-up.

Semi-conductor Tracker

The Semi-Conductor Tracker (SCT) is the next tracking system following the Pixel detector. Similar to the Pixel detector, the SCT consists of 4 layers of barrel detectors and 9 disk detectors at each end-cap region. Each barrel/disk is made of SCT modules containing double-sided silicon strips, measuring $80 \mu\text{m}$ wide and 12 cm long¹. Strips are positioned parallel (perpendicular) to the beam axis in the barrel (end-cap) region. Because a single strip can only provide spatial information in $(r-\phi)$ direction in barrel and $(z-\phi)$ direction in end-cap region, double-sided strips are displaced by a relative angle of 40 mrad to provide three-dimensional spatial measurements of charged particles. The SCT has a spatial resolution of $17 \mu\text{m}$ in radial direction and $580 \mu\text{m}$ in z direction. The information collected by the SCT is used for charge and transverse momentum measurements and reconstruction of vertices.

Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is the outermost tracking system in the ID, covering the region up to $|\eta| < 2.0$. The TRT barrel region is covered by 52,544 straw tubes aligned parallel to the beam axis. The TRT end-cap region is covered by 122,800 straw tubes aligned in radial direction. Each straw tube is filled with a Xe-based gas mixture, and a wire is placed at the center of the tube, acting as an anode. When a charged particle traverses the

¹There are two versions of SCT strips in end-cap modules with lengths of 12 cm and 7 cm .

detector, it ionizes the gas mixture inside straws, producing a cascade of electrons. These electrons from the ionization drift toward the center wire, creating signal for the readout with the intrinsic resolution of a single straw tube of $\sim 120\mu\text{m}$ [32].

The TRT also provides important information on particle identification. The spaces between straws are filled with polymer fiber (barrels) and foils (end-caps) for the production of transition radiation. When a highly relativistic charged particle passes through them, photons may be emitted by transition radiation, and these photons can be absorbed by the gas mixture, resulting in higher readout signals than usual, called high-threshold hits. The effect is stronger for electrons due to larger relativistic factor ($\gamma = E/m$) than particles with a lower boost such as hadrons. Therefore, the high-threshold hits in the TRT can be used for electron/pion identification [33].

2.2.3 The Calorimeters

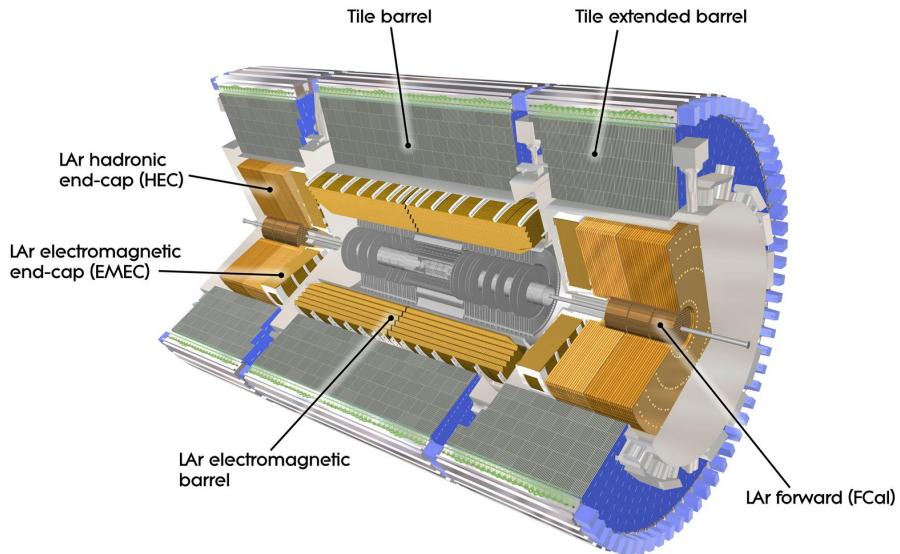


Figure 2.3: The ATLAS calorimeter system.

The ATLAS calorimetry system, shown in Figure 2.3, consists of two sub-systems, the Liquid Argon (LAr) calorimeters [34] and the tile calorimeters (TileCals) [35]. The calorimeters are designed to measure the energy deposited by a particle as it traverse through the detector, and the signals from calorimeters are used for the trigger system. Based on its

usage, the calorimeters can be grouped into two sets of calorimeters: the Electromagnetic (EM) calorimeters and hadronic calorimeters.

Electromagnetic Calorimeter

The EM calorimeters (EMC) are located outside the ID and the solenoid magnet, and they are designed to measure the energy deposition from electrons and photons. They are composed of two LAr calorimeters, the EM End-Cap calorimeter (EMEC) covering the region of $|\eta| < 1.475$ and the EM Barrel (EMB) calorimeter covering the region of $1.375 < |\eta| < 3.2$. The LAr calorimeters are composed of layers of high density material (Pb) and LAr sampling layer interspaced for absorption of electron/photons and energy measurement, respectively. The first layer of the LAr calorimeters is called *presampler* which is a thin layer of liquid argon without absorber in front, and it is used to correct for the energy loss before a particle reaches the calorimeter. The LAr calorimeters are called sampling calorimeters because only a small fraction of the deposited energy is measured by sampling layers.

When an electron or a photon enters the calorimeters, the electron/photon interacts with the absorber layers, creating the initial EM shower via bremsstrahlung and pair-production. The EM shower is amplified and collected by the sampling layers. The EM calorimeters have the minimum number of radiation length of $24 X_0$ [36].

Hadronic Calorimeter

Hadrons are less likely to produce bremsstrahlung radiation due to heavier mass, and they can traverse through the EMC without losing significant energy. Therefore, the hadronic calorimeters are located outside the EMC to measure the energy of hadrons penetrating the EMC. The hadron calorimeters are composed of both LAr calorimeters and TileCals.

The hadronic LAr calorimeters consists of two parts, the hadronic end-cap calorimeter (HEC) covering the region of $1.5 < |\eta| < 3.2$ and the forward calorimeter (FCAL) covering the region of $3.1 < |\eta| < 4.9$. The principle of hadronic LAr calorimeters is the same as EM LAr calorimeters. The HEC is divided into four longitudinal layers with copper absorber. The FCAL consists of one EM layer which uses copper as absorber and two hadronic layers with tungsten as passive material. When a hadron enters the hadronic LAr calorimeters, the particle interacts with nuclei of the absorber material via strong force, creating a hadronic shower. The hadronic shower is sampled by sampling layers.

TileCals are designed to cover the central barrel region ($|\eta| < 1.0$) and the extended barrel region ($0.8 < |\eta| < 1.7$). The TileCals are made of alternating layers of iron and scintillating

tiles. Hadrons entering the absorber layers produce hadronic showers, and the secondary particles from the showers interact with the scintillating tiles to produce lights. The photons are delivered to photomultipliers via wave-length shifting fibers and registered as calorimeter cluster hit.

The TileCals, combined with the hadronic LAr calorimeters, provide precise measurement of hadrons, jets, taus, and missing transverse energy (E_T^{miss}).

2.2.4 The Muon Spectrometer

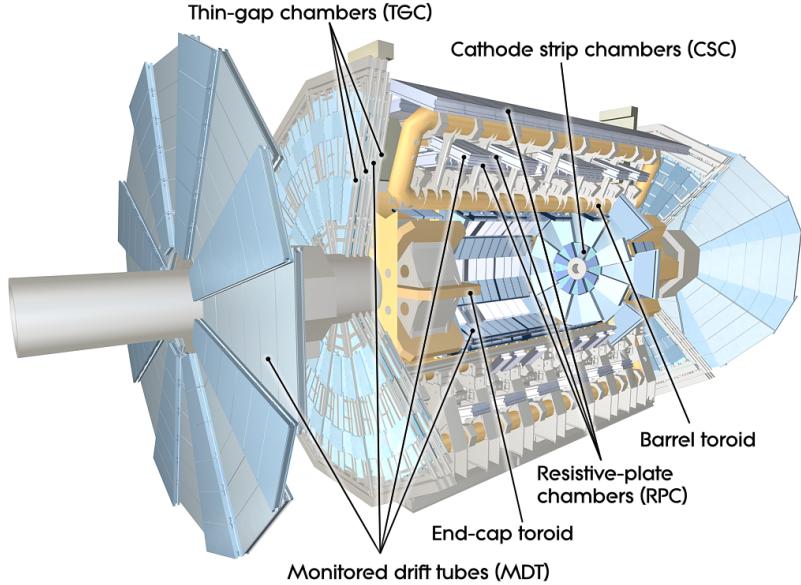


Figure 2.4: The ATLAS Muon Spectrometer

The Muon Spectrometer (MS) is the outermost detector in the ATLAS detector, responsible for muon identification, momentum measurements, and muon trigger information. The MS is designed to provide high p_T momentum measurement with resolution of $\sigma_{p_T}/p_T = 10\%$, independent from the ID. The MS consists of four sub-detector systems. The Resistive Plate Chambers (RPCs) and the Thin Gap Chambers (TGCs) are used for muon triggering. The Monitored Drift Tubes (MDTs) and the Cathode Strip Chambers (CSCs) allow precise tracking and momentum measurements. The MS barrel region covers the region of $|\eta| < 1$, and the coverage is extended to $|\eta| < 2.7$ in the end-cap. The magnetic field is applied with an average 0.5 T [37] by a system of a large toroidal magnet (barrel) and two smaller

toroidal magnets (end-cap). A layout of the MS is shown in Figure 2.4.

Monitored Drift Tube Chambers

The MDT chambers provide precision momentum measurements using chambers of drift tubes filled with a gas mixture of Ar (97%) and CO₂(3%). The barrel MDT chambers are arranged in three layers, covering the region of $|\eta| < 1.1$. The end-cap MDT chambers are arranged in three wheels, covering the region of $1.1 < |\eta| < 2.7$. Each drift tube measures 3 cm in a diameter, and a tungsten-rhenium wire is placed at the center as an anode. Each chamber has 6-8 layers of drift tubes. The principal of particle detection is similar to the TRT, but the drift tubes are arranged perpendicular to the beam axis in the barrel layers and tangential in the end-cap layers. This configuration allows the MDT to measure the curvature of a muon in η - z plane under the toroidal magnetic field.

Cathode Strip Chambers

The CSCs are located on the innermost wheel of the end-caps, covering the region of $2.0 < |\eta| < 2.7$. In this region, the MDTs would not operate properly due to the high rates of muons coming from the beam pipe. Instead, sixteen CSCs on each end-cap provide precise tracking for high density muons with the resolution of 60 μm in η - z plane and 5 mm in the radial direction. The CSCs are multi-wire proportional chambers with segmented cathode strips in alternating alignment. The multi-wires are aligned in the radial direction, and the strips are aligned perpendicular or parallel to the wires to provide 2 dimensional measurements in both η and ϕ directions.

Resistive Plate Chambers

The RPCs provide trigger capability for the muon trigger and measurements in η , ϕ coordinates in the barrel region. There are three RPCs arranged in concentric cylindrical shells around the beam axis. The two inner RPCs are placed at the radii of 5 m and 7.5 m to provide the low- p_T trigger information. The outer RPCs are installed at the radius of 10 m to provide high- p_T trigger information. Each chamber consists of two parallel resistive plots separated by a 2 mm gap filled with a gas mixture based on C₂H₂F₄. A muon track passing through the RPCs ionizes the gas, and the signal is multiplied and read out by each chamber, providing 6 measurements for each track.

Thin Gap Chambers

The TGCs are designed to provide trigger information and ϕ measurements (non-bending direction) in the end-cap region. Similar to the CSCs, the TGCs are made of multi-wire proportional chambers filled with a gas mixture of 55% CO₂ and 45% C₅H₁₂. The strips are oriented in radial direction, allowing measurements in ϕ . The TCGs consists of 4 layers of chambers on each end-cap, covering the region of $1 < |\eta| < 2.7$.

2.2.5 The ATLAS Magnet

The ATLAS detector has three major superconducting magnet systems surrounding the ID and the MS: the Central Solenoid magnet and the Barrel/End-cap Toroid magnets.

Central Solenoid Magnet

The Central Solenoid magnet surrounds the ID, producing a 2 T magnetic field. The solenoid is designed to bend the trajectory of a charged particle in $r\text{-}\phi$ plane. The curvatures of charged particles are used for the measurements of charge-to-momentum ratio. The solenoid magnet measures 2.4 m in diameter and 5.3 m in length, and 7.73 kA of current is applied to generate the solenoidal magnetic field.

Toroid Magnets

In the outer region of the ATLAS detector, two superconducting toroid magnet systems are used to generate a magnetic field within the MS. The Barrel Toroid are composed of 8 separate coils made of Al/NbTi/Cu conductor with 120 turns. The toroid measures 20.1 m in diameter and 25.3 m in length. The End-cap Toroid has 8 coils with 116 turns, and the coils are made of the same material as the Barrel Toroid. The nominal current of 20.5 kA is applied to generate a magnetic field in the range of 1 to 2 T with the field integral between 2 to 8 Tm.

2.3 The ATLAS Trigger System

The ATLAS trigger system is designed to select interesting events from raw event data at high rate, generated by pp collisions. In Run 2, the LHC collide proton bunches every 25 ns, resulting in about a billion pp collisions per second at $\langle \mu \rangle = 24.9$ (in 2016). Due to the

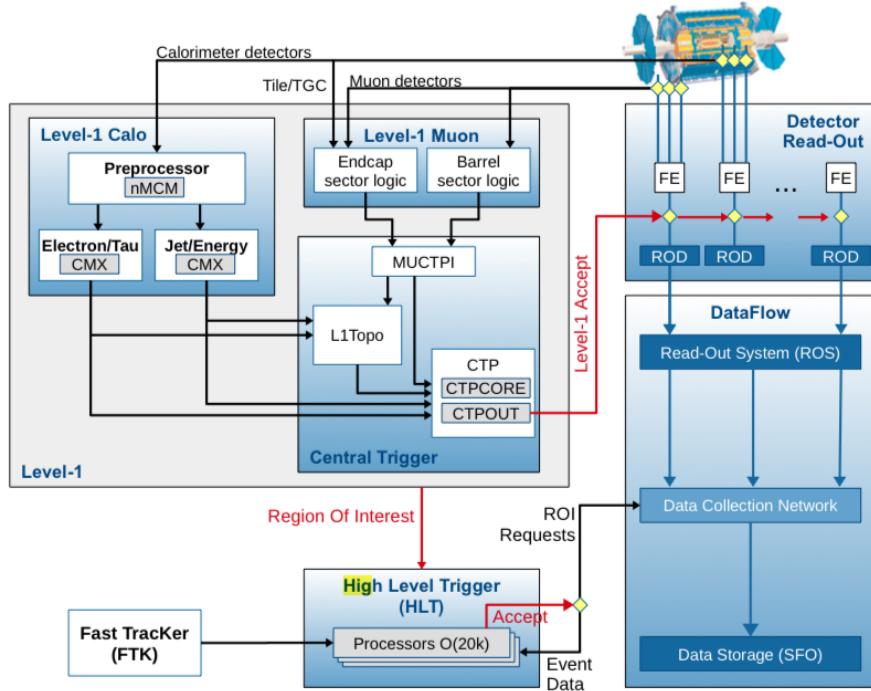


Figure 2.5: Layout of the ATLAS Trigger and data acquisition system in Run 2.

limited bandwidth and computing resources, it is impossible to record all events from the collisions. Therefore, the ATLAS trigger system is implemented to reduce the data taking rate from 40 MHz to 100 kHz. In Run 2, several upgrades have been performed in both hardware and software to maintain data quality in the environment with increasing pile-up, higher instantaneous luminosity at the center-of-mass energy of $\sqrt{s} = 13$ TeV.

The trigger system in Run 2 consists of a hardware-based Layer 1 (L1) trigger and a software-based High Level Trigger (HLT). Figure 2.5 shows the ATLAS trigger and data acquisition system in Run 2. The events accepted by the trigger system are further processed by the Data Acquisition (DAQ) system where the information from front-end electronics of each detector component are used to build an individual event. The reconstructed events from DAQ are sent to Data Storage (SFO) for permanent storage.

2.3.1 Level 1 Trigger

The L1 trigger is a hardware-based trigger system that operates at the maximum rate of 100 kHz [38]. The main components of the L1 trigger consist of the L1 calorimeter trigger system and the L1 muon trigger system. The L1 trigger uses custom electronics to make

fast decisions and find regions of interest (RoI) in the detector where potentially interesting activities are registered in the calorimeters or the MS.

A list of trigger selection is developed based on the physics goal of the collaboration and the needs of individual analyses. The list is called the Trigger Menu [39]. The L1 trigger accepts the events with high p_T tracks, jets, or large E_T^{miss} that satisfies one of the trigger menu. The events accepted by the L1 trigger is passed to the software-based trigger system.

2.3.2 High Level Trigger

In Run 2, two software-based trigger systems, the Level 2 trigger and the Event Filter, are combined into a single software trigger system, called the High Level Trigger(HLT) . The HLT makes the decision on events based on full information from the detector read-out in the RoI passed by the L1 trigger. This includes a fast reconstruction of the inner detector tracks. The HLT has the average output rate of 1 kHz [38], constrained by data storage limitation.

Chapter 3

Z' RECONSTRUCTION

The experimental signature in the search for long-lived Z' is characterized by a high- p_T dilepton vertex, displaced (>2 mm) from the primary vertex in transverse plane, referred a *displaced vertex*. In this chapter, the reconstruction of displaced vertices in the ATLAS ID is described.

3.1 Track Reconstruction in the Inner Detector

Track reconstruction in the ATLAS uses pattern recognition algorithms to reconstruct the trajectories of charged particles, referred as *track*. When a charged particle traverse through the ID, the particle interact with the sub-detectors of the ID (Pixel, SCT, and TRT), leaving raw detector signals. The raw signals are digitized and registered as detector *hits*, and these detector hits are used for track reconstruction.

3.1.1 Standard Tracking

The standard ATLAS track reconstruction is the main track reconstruction algorithm used in the ATLAS experiment. In the first stage of the track reconstruction, detector hits from the Pixel or the SCT detector are used to create *track seeds*, collections of silicon hits used for the initial track finding. If a track seed passes certain quality criteria, including a p_T and impact parameter selection, the track seed is extended to the outer part of the ID using a window search and pattern recognition algorithms. The extended tracks are evaluated based on p_T , number of hits, and impact parameters, and only the tracks satisfying the standard track selections are stored in the track collection. Figure 3.2 illustrates detector hits and reconstructed tracks in the ID. The important standard track selections is summarized in

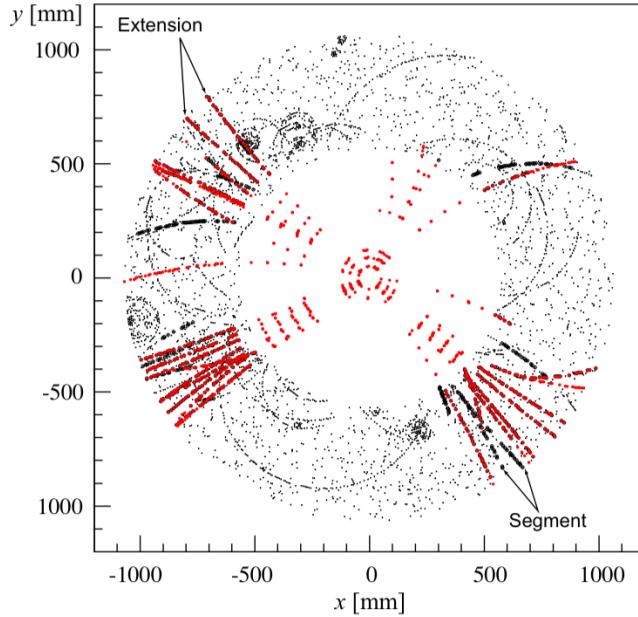


Figure 3.1: Illustration of detector hits and reconstructed tracks in the ID. The bright colors represent the detector hits associated with reconstructed tracks [1].

Figure 3.2:

Table 3.1 [40].

Tracks are described by five parameters and a reference point, using a perigee representation. The parameters are the transverse (longitudinal) impact parameter d_0 (z_0), the azimuthal angle ϕ , the polar angle θ , and the charge-to-momentum ratio, q/p . The average position of the pp interaction, referred as beamspot, is used as the reference point for the track representation [41].

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $ \eta $	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7

Table 3.1: Important track selection in the standard and the LRT algorithms.

3.1.2 Large Radius Tracking

The standard track reconstruction is proven to be very efficient in Run 2 with the tracking efficiency $> 90\%$ [42]. However, the tracking algorithm is optimized for primary charged particles promptly produced from pp collisions, and the strict requirements on the impact parameters, d_0 and z_0 potentially limit the tracking efficiency for the charged particles with large impact parameters ($|d_0| > 2$ mm). Therefore, a dedicated track reconstruction algorithm, referred to as the large radius tracking (LRT), is developed to improve the track reconstruction efficiency for the tracks highly displaced from the primary vertex.

The LRT is performed in a sequence, following the standard tracking. It follows the same reconstruction strategy as the standard tracking, but there are a few important differences between the standard tracking and the LRT.

- The pattern recognition algorithms in the LRT only use *un-used* hits, the silicon hits that have not been used in the standard tracking, in creating and extending track seeds.
- The requirements on tracks such as d_0 , z_0 , and number of hits are relaxed.

Tracks reconstructed by the LRT using un-used hits are required to pass certain criteria such as minimum p_T and number of detector hits, and the selected tracks are merged into the standard track collection for the next step of reconstruction. The track selections in the LRT are summarized and compared with the standard track reconstruction in Table 3.1. The combined track collection is used as an input for the lepton reconstruction and identification and secondary vertex reconstruction. More details on the LRT can be found in Ref. [40].

Combined with the standard track reconstruction, the LRT provides overall efficiency of 90% or above for the particles that satisfy the fiducial selections in Table 3.2 with a displacement in the transverse plane up to 300 mm.

Fiducial Selections		
r_{prod}	<	300 mm
$ \eta $	<	5
p_T	>	1 GeV
Number of silicon hits	\geq	7

Table 3.2: Fiducial selections on particles for tracking efficiency measurements.

3.2 Electron Reconstruction

Electrons are characterized by energy deposits in the EM calorimeter and the associated reconstructed tracks in the ID. The electron reconstruction algorithm uses the energy deposits with total transverse energy > 2.5 GeV in a window size of 0.075×0.125 in (η, ϕ) to reconstruct EM clusters. The EM clusters are associated with tracks within the same RoI, $|\Delta\eta| < 0.05$ and $|\Delta\phi| < 0.1$ where the effect of bremsstrahlung is taken into account [43]. In the absence of a matching track, the EM cluster is classified as a photon candidate. The associated pairs of tracks and clusters are refitted to create electron candidates. Additional electron requirements, including likelihood-based identification criteria, are imposed on the electron candidates for reconstruction of electrons.

3.3 Muon Reconstruction

Muons leave very small energy deposits in the calorimeter as they traverse through the detector due to the relatively larger mass, given that the probability of bremsstrahlung is $\propto 1/m^2$. However, they leave tracks in both the ID and the MS, referred as inner detector (ID) tracks and muon standalone (MS) tracks. The muon reconstruction algorithm uses MS tracks as seeds, and the MS tracks are extrapolated to the ID for the association with ID tracks. A *combined muon* track is created if a MS track is successfully associated with an ID track after the momentum correction for the energy loss from the interaction with the detector material. There are other types of reconstructed muons such as standalone muons, segment-tagged muons, and calorimeter-tagged muons [44]. However, these types of muons are not considered in this analysis as they do not have associated ID tracks which are required for the reconstruction of displaced vertices.

By default, muons are required to have a minimum number of Pixel, SCT hits and small transverse impact parameters. This is not optimal for the searches that aim to detect displaced vertices as the decay products of displaced vertices tend to have large impact parameters (d_0, z_0) and missing hits in the inner layers of the detector. Therefore, the requirements on d_0 and Pixel hits are removed. Also minimum SCT hits on muon tracks are lowered to 2.

3.4 Secondary Vertex Reconstruction

In the LHC, when two proton bunches collide, several different vertex topologies arise. The primary vertex and several pile-up vertices are formed along the beam line, and the vertices

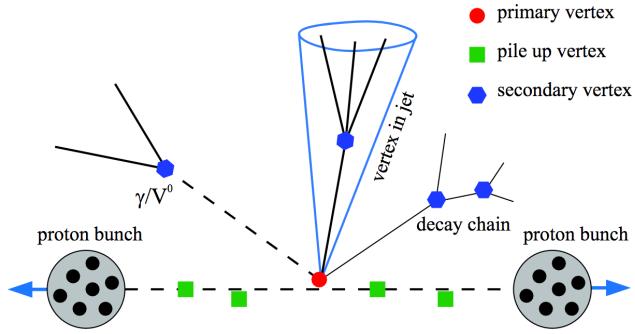


Figure 3.3: Important vertex topologies in pp collisions: primary, pile-up, and secondary vertices.

from photon conversion or long-lived particles are formed displaced from the primary vertex as shown in Figure 3.3. These displaced vertices are referred as secondary vertices. In the search for long-lived Z' in dilepton decay channel, the decay products of long-lived particles can be reconstructed as a secondary vertex.

The secondary vertex reconstruction is based on the primary vertex reconstruction algorithm [45] and was originally developed for the study of material mapping of the ID in Run I. The algorithm was updated for several long-lived particle searches in Run 2.

In the first stage, track are selected using the requirements on track parameters and hit patterns shown in Table 3.3. The tracks reconstructed by both the standard track reconstruction and the LRT are used as input. The tracks passing the track requirements are used to create two-track vertices, based on the closeness of two tracks in the space. This process results in a large number of fake vertices. The fake vertices are rejected by considering the location of a vertex and hit patterns of the tracks associated with the vertex. A vertex is rejected if the associated tracks have any hits at a radius smaller than the vertex position. Two-track vertices passing the fake rejection are refitted using a Kalman Filter for precise vertex position measurements, and track parameters are calculated with respect to the secondary vertex.

The two-track vertices reconstructed by the secondary vertex reconstruction serves as the primary analysis object in this thesis.

Variable	Cut
p_T (GeV)	> 1.0
χ^2/DOF	< 50
d_0 (mm)	2.0 - 300.0
z_0 (mm)	< 1500.0
SCT hits	≥ 2
Si shared hits	≤ 2
Pixel and TRT hits	TRT hits > 0 or Pixel hits ≥ 2

Table 3.3: Track requirements for secondary vertex reconstruction.

Chapter 4

ANALYSIS OVERVIEW

This thesis presents a search for a heavy long-lived resonance decaying to a dilepton pair, $\mu^+\mu^-$, e^+e^- , or $e^\pm\mu^\mp$ within the ATLAS ID. The analysis uses 32.8 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ collected in 2016 in the ATLAS detector. The long-lived particle (LLP) is referred as Z' but with no assumption on Z' production mechanism for a model-independent search.

There have been several searches for the LLPs produced in pp collisions in Run I at $\sqrt{s} = 8 \text{ TeV}$, including the search for displaced hadronic jet [46], displaced heavy flavors [47], or multi-track displaced vertex [48], and no significant excess was observed. The signature considered in this analysis is distinct from the previous searches, and it is one of the first efforts in the ATLAS experiment to search for a generic displaced vertex signature decaying to a dilepton pair. This analysis focuses on interpreting the LLPs decaying to displaced dilepton vertices in the context of model-independent, exotic resonance search.

In this search, a special setup (described in Section 3.1.2) of data reprocessing and reconstruction is used in order to gain sensitivity for the non-conventional signature of LLPs. The special setup allows the reconstruction of tracks with large impact parameters and secondary vertices significantly displaced from primary vertices.

Chapter 5

DATA AND MC SAMPLES

5.1 Data samples

The analysis uses the 2016 pp collisions data (periods A-L) with the integrated luminosity of 32.8 fb^{-1} . In this search, because the standard ATLAS track reconstruction does not provide good sensitivity for long-lived particles, a dedicated physics stream, `DRAW_RPVLL`, is used to reconstruct events using the non-standard reconstruction as described in Chapter 3. The stream is used in several Exotics and SUSY analyses, searching for long-lived particles.

In this stream, a subset of events from the main physics stream is selected by `RPVLL` filters. The filters select events using the HLT and offline selections configured for each analysis. The triggers and offline selection used in this search is discussed in Chapter 6. The selected events are passed downstream for reconstruction. The data is in `RAW` format so that low-level information such as detector hits can be used for the special reconstruction algorithms to reconstruct displaced tracks and vertices.

The events passing HLTs are processed by a sequence of simulation and reconstruction algorithms with varying configurations, and the ATLAS metadata interface (AMI) tags are used to specify the configurations to be used for a data processing chain. In this analysis, the events are centrally processed with AMI tag `r8669` in which the dedicated track reconstruction algorithm, the LRT, and the secondary vertex reconstruction algorithm are enabled to reconstruct displaced tracks and vertices, respectively. The output of `DRAW_RPVLL` stream is in `DAOD_RPVLL` format which is a standard `xAOD` data format with additional displaced tracks and secondary vertices reconstructed.

The `DAOD_RPVLL` is further processed to produce the `DAOD_SUSY15` derivation for data

reduction and software fixes on analysis objects such as energy calibration ², as recommended by the Analysis Model Study Group (AMSG) [49]. Table 5.1 summarizes datasets used in this search.

Format	Dataset
DRAW_RPVLL	data16_13TeV.*.physics_Main.merge.DRAW_RPVLL.f*_m*
DAOD_RPVLL	data16_13TeV.*.physics_Main.recon.DAOD_RPVLL.f*_r8669
DAOD_SUSY15	data16_13TeV.*.physics_Main.recon.DAOD_RPVLL.f*_r8669_p2950

Table 5.1: Dataset used in DRAW_RPVLL, DAOD_RPVLL, and DAOD_SUSY15 format.

This search uses a modified version of the standard `GoodRunsList` because a small number of events selected by `DRAW_RPVLL` was not reconstructed successfully. The corresponding luminosity blocks were removed from the `GoodRunsList`³.

The tag and probe studies of Section 7.1 are performed on the standard xAOD dataset using derivations of the performance groups, given in Table 5.2.

Format	Dataset
DAOD_EGAM1	data16_13TeV.*.physics_Main.PhysCont.DAOD_EGAM1.grp16_v01_p3013
DAOD_MUON1	data16_13TeV.*.physics_Main.PhysCont.DAOD_MUON1.grp16_v01_p3043

Table 5.2: Datasets used for tag and probe studies.

5.2 MC samples

5.2.1 Signal samples

The long-lived Z' is generated using PYTHIA 6.4 [50] with the NNPDF23LO PDF set and the min-bias tune A14. In this signal samples, Z' is singly produced from $q\bar{q}$ scattering and decays to a $\mu\mu$, ee , or $e\mu$ pair. The proper lifetime, $c\tau$, is set to 100, 250, or 500 mm. The mass of Z' is set between 100 and 1000 GeV. A width based on relativistic Breit-Wigner is assumed for the new resonance. A sample of 20k events are generated for each mass and

²Software fixes are released by The ATLAS collaboration in the form of `AODfix`.

³data16_13TeV.periodAllYear_DetStatus-v83-pro20-15_DQDefects-00-02-04_PHYS_StandardGRL_All_Good\25ns_DAOD_RPVLL_r8669.xml

lifetime. Table 5.3 summarizes dataset identifiers (DIDs), mass, width, and lifetime of the signal MC samples used in this search.

$m_{Z'}$ (GeV)	Γ (GeV)	$c\tau$ (mm)	DID		
			$\mu\mu$	ee	$e\mu$
100	2.8	100	308264	309539	309554
100	2.8	250	308265	309540	309555
100	2.8	500	308266	309541	309556
250	6.9	100	301911	309542	309557
250	6.9	250	301912	309543	309558
250	6.9	500	301913	309544	309559
500	14.7	100	301914	309545	309560
500	14.7	250	301915	309546	309561
500	14.7	500	301916	309547	309562
750	23.0	100	308285	309548	309563
750	23.0	250	308286	309549	309564
750	23.0	500	308287	309550	309565
1000	31.0	100	301917	309551	309566
1000	31.0	250	301918	309552	309567
1000	31.0	500	301919	309553	309568

Table 5.3: Mass, lifetime, and DID of the signal MC samples.

The signal MC samples generated using PYTHIA are processed to include detector simulation using the AMI tags `s2698` and `s2726`. The samples are overlaid with simulated minimum-bias events to model multiple interactions (pile-up) in data samples. In the signal MC samples, the average number of pile-ups, $\langle \mu \rangle$, ranges from 10 to 40 with small number of events having $\langle \mu \rangle < 10$. The difference in the $\langle \mu \rangle$ distributions between MC and data samples are corrected for by pile-up reweighting. The resulting MC samples are reconstructed using AMI tag `r8788`.

In the reconstruction process, the LRT and the secondary vertex reconstruction algorithms are used with the same configuration as data samples to reconstruct displaced tracks and vertices. The reconstructed events are stored in `DAOD_RPVLL`, and the samples are processed to produce the `DAOD_SUSY15` derivation for data reduction and software fixes on analysis objects.

The representative plots of generator-level p_T and η distributions of Z' and the muons from the decay of Z' , referred as *signal* muons, are shown in Figure 5.1 using the signal MC samples with $m = 500, 1000$ GeV and $c\tau = 100$ mm. The signal MC samples with ee and $e\mu$

final states produce similar distributions as shown in Appendix A.

The η distribution of signal muons shows that most of the signal muons are produced within the detector acceptance ($\eta < 2.7$). The characteristic upper edge in the p_T spectrum is related to the Z' mass.

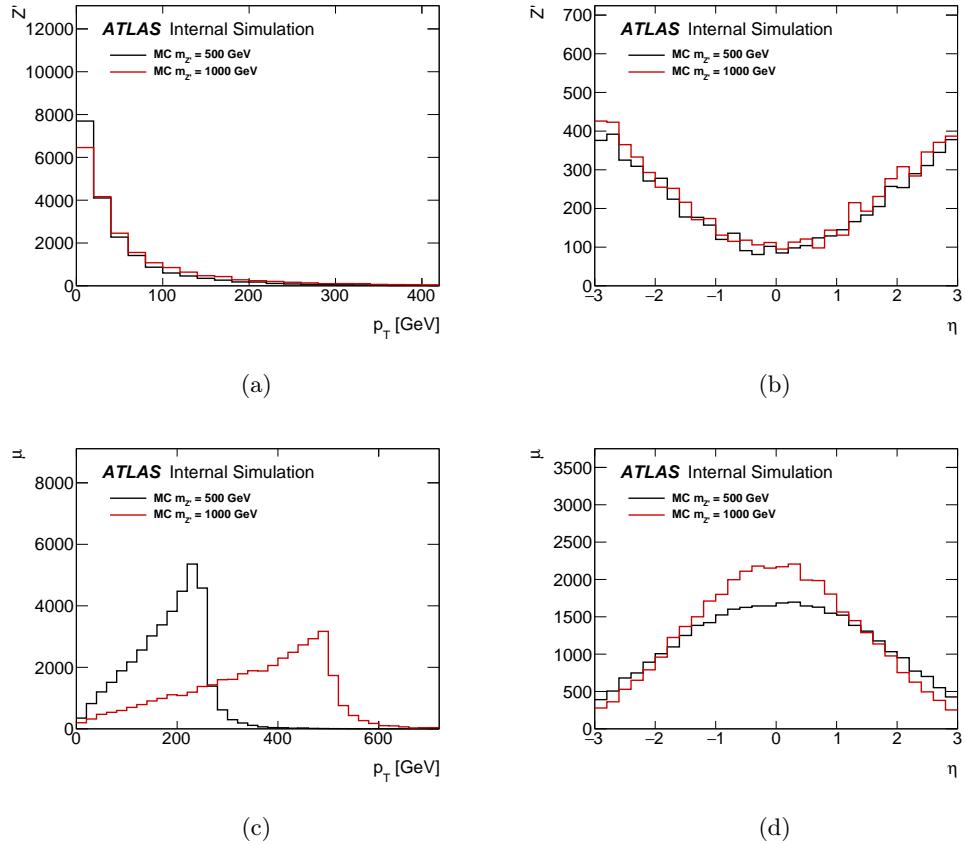


Figure 5.1: The representative plots of generator-level (a) p_T and (b) η distributions of Z' , and (c), (d) are the corresponding distributions for the signal muons. The signal MC samples are generated with $m = 500, 1000$ GeV, and $c\tau = 100$ mm.

5.2.2 Background MC samples

In this analysis, backgrounds are estimated from data because most of the backgrounds are expected to be originated from non-collision processes such as cosmic rays or random-crossing of tracks.

However, SM background samples are used to study the performance of random-crossing background estimation (Section 8.2) and to estimate the systematic uncertainties in vertexing and tracking (Section 9.1). The $t\bar{t}$ samples are generated for QCD background study using **SHERPA** with the **NNPDF30NNLO** PDF set. The samples with leptonic decay of di-boson (ZZ , WW , $W^\pm Z$) are generated using **SHERPA** with the **CT10** PDF set. The di-jet samples (JZ3W-JZ7W) are generated in slices of leading jet p_T (160-400, 400-800, 800-1300, 1300-1800, 1800-2500 GeV) using **PYTHIA8** with **NNPDF23L0** PDF set. These samples are sufficient for testing purposes, as they contain high- p_T isolated leptons (from W boson decays) and leptons and displaced tracks in b-jets, in addition to tracks from pile-up vertices.

The SM background samples are reprocessed using the same configuration as the signal MC sample for consistency. The background MC samples used for background and systematic uncertainty estimations are summarized in Table 5.4.

Process	DID	σ (pb)	Events (10^6)	$\mathcal{L}_{Int}(\text{fb}^{-1})$
$t\bar{t}$	410252	76.3	0.70	9.17
$ZZ \rightarrow \ell\ell\ell\ell$	361063	12.8	0.12	9.30
$W^-Z \rightarrow \ell\ell\ell\nu$	361064	1.84	0.02	10.9
$W^+Z \rightarrow \ell\ell\nu\nu$	361066	2.56	0.025	9.77
$WW \rightarrow \ell\ell\nu\nu$	361068	14.0	0.13	9.29
JZ3W	361023	$2.65 \cdot 10^7$	0.20	$< 10^{-5}$
JZ4W	361024	0.255	0.20	784
JZ5W	361025	0.455	0.20	440
JZ6W	361026	258	0.20	0.775
JZ7W	361027	16.2	0.10	0.617

Table 5.4: Background MC samples used in the study of random-crossing background and in the estimation of tracking and vertexing systematic uncertainty.

Additional samples are used without the special reconstruction to study the efficiency of the triggers using tag-and-probe method (Section 7.1). These samples are given in Table 5.5.

Format	Dataset
DAOD_EGAM1	mc15_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.merge.DAOD_EGAM1.e3601_s2576_s2132_r7725_r7676_p3012
DAOD_MUON1	mc15_13TeV.361107.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zmumu.merge.DAOD_MUON1.e3601_s2576_s2132_r7725_r7676_p3045

Table 5.5: Background MC samples without the LRT used for tag and probe studies.

Chapter 6

SIGNAL SELECTION

The primary physics objects of this analysis are muons, electrons, and dilepton displaced vertices (DVs). In this section, the signal selection criteria for these physics objects are described.

6.1 Event preselection

Events are pre-selected in data processing using a combination of offline triggers and custom filters, called `DRAW_RPVLL`. The selected events from the main physics stream are reprocessed for the special reconstruction. The filters are designed to select events containing displaced vertex candidates while maintaining reasonably low filter rates (<30 Hz). Single photon (γ), single electron (e), di-photon ($\gamma\gamma$), di-electron (e^+e^-), and the combination of photon and electron ($e\gamma$) filters are used to select events with e^+e^- or $e^\pm\mu^\mp$ candidates of interest. Single μ filter is used to select events with $\mu^+\mu^-$ or $e^\pm\mu^\mp$ candidates of interest.

The filters require events to pass one of the HLTs listed in Table 6.1. Most of the HLTs developed in the ATLAS are designed for prompt searches, and there are implicit requirements on particles so that the extrapolation of a particle points back to the IP. Therefore, the triggers with no requirement on ID tracks are used to increase the sensitivity to electrons and muons with large transverse and longitudinal impact parameters, d_0 and z_0 . Consequently, the muon trigger that only uses the muon spectrometer information is used to trigger displaced muons. The photon triggers are used to trigger displaced electrons so that only the calorimeter information is used.

In addition to the HLT requirements, each filter requires offline selections on particles such as p_T , η , and d_0 . Single photon (γ) or electron (e) filter requires a leading photon

Description	Trigger
Single photon	HLT_g140_loose
Di-photon	HLT_2g50_loose
Single muon	HLT_mu60_0eta105_msonly

Table 6.1: HLts used to select events in `DRAW_RPVLL` filter. Single photon trigger requires one photon with $p_T > 140$ GeV. Di-photon trigger requires two photons with $p_T > 50$ GeV. Single muon trigger requires one muon with $p_T > 60$ within $0 < |\eta| < 1.05$ using MS information only.

or electron, respectively, with $p_T > 150$ GeV, $\eta < 2.5$, and $d_0 > 2.0$ mm. These filters also require a second photon or lepton with $p_T > 10$ GeV and $\eta < 2.5$ to keep the filter rate reasonably low. Single muon μ filter requires a muon with $p_T > 60$ GeV, $\eta < 2.5$, and $d_0 > 1.5$ mm. Di-photon ($\gamma\gamma$), di-electron (e^+e^-), and the combination of photon and electron ($e\gamma$) filters require two photons/leptons with $p_T > 50$ GeV, $\eta < 2.5$, and $d_0 > 2.0$ mm. The offline selection is summarized in Table 6.2.

Filter	Leading			Second		
	p_T (GeV)	$ \eta $	d_0 (mm)	p_T (GeV)	$ \eta $	d_0 (mm)
γ, e	> 150	< 2.5	> 2.0	> 10	< 2.5	-
μ	> 60	< 2.5	> 1.5	-	-	-
$\gamma\gamma, e^+e^-, e\gamma$	> 50	< 2.5	> 2.0	> 50	< 2.5	> 2.0

Table 6.2: RPVLL filter offline selection on photon and leptons. Single photon (γ) or electron (e) filter requires a leading photon or electron, respectively, with $p_T > 150$ GeV, $\eta < 2.5$, and $d_0 > 2.0$ mm and a second photon or lepton with $p_T > 10$ GeV, $\eta < 2.5$. Single muon μ filter requires a muon with $p_T > 60$ GeV, $\eta < 2.5$, and $d_0 > 1.5$ mm. Di-photon ($\gamma\gamma$), di-electron (e^+e^-), and the combination of photon and electron ($e\gamma$) filters require a photon or lepton with $p_T > 50$ GeV, $\eta < 2.5$, and $d_0 > 2.0$ mm.

The event selected by the RPVLL filters are passed downstream for the special reconstruction process, and the physics objects such as electron, muon, and secondary vertices are reconstructed for analysis,

6.1.1 Event selection

At analysis-level, minimum requirements are placed on events based on the quality of events, completeness of the corresponding luminosity blocks, primary vertex, and HLts used in this

analysis. In addition, cosmic veto is applied to reject events with back-to-back muons. The event selection is described below.

- `GoodRunsList` removes events from incomplete luminosity blocks.
- Event cleaning removes corrupted/bad events due to problems in TileCal, LAr calorimeter noise bursts, and detector downtimes.
- Events are required to pass one of the HLTs listed in Table 6.1.
- At least one primary vertex is required along the beam line ($z < 200$ mm).
- Events are rejected if there is a pair of leptons with $R_{\text{CR}} < 0.01$ where $R_{\text{CR}} = \sqrt{(\Delta\phi - \pi)^2 + (\Sigma\eta)^2}$.

The event selection is summarized in Table 6.5.

6.1.2 Muon and electron requirements

The analysis searches for displaced vertices with two leptonic tracks, $\mu^+\mu^-$, e^+e^- , and $e^\pm\mu^\mp$. Prior to applying the vertex level selections, tracks from vertices are required pass muon or electron selections based on track quality, kinematics, and lepton identification criteria.

Electron requirements are based on the recommendations from the Electron-Gamma (EG) group with a few optimization for electrons with large impact parameters. Electrons are rejected if there is a bad cluster associated with an electron. Basic kinematic cuts are applied to electrons, $|\eta| < 2.47$ and $p_T > 10$ GeV. The EG group provides several electron identification criteria, called working points, based on a likelihood discriminant to suppress background electrons originating from photon conversions and heavy flavour decays. In this analysis, the electron `LooseLH` working point is used, but the requirements on d_0 and silicon hits are removed to improve electron detection efficiency at large impact parameters.

Muon requirements are based on the recommendations from Muon Combined Performance group with similar optimizations as electrons. Muon `Loose` working point is used for the identification criteria, and a fiducial cut, $|\eta| < 2.5$, and kinematic cut, $p_T > 10$ GeV, are applied to muons. The requirements on Pixel hits are removed to improve muon detection efficiency at large impact parameters. Muons are required to have an associated ID track for vertex reconstruction. In case of MC samples, muon momentum resolution and scale correction are applied to the simulated muons for better agreement between data and simulation [44].

Overlap removal is applied to both muons and electrons to ensure that a ID track is associated with only one muon or electron. The muon and electron requirements are summarized in Table 6.3.

Muon	Overlap removal Muon Loose (no requirement on Pixel hits) $ \eta < 2.5$ $p_T > 10.0$ GeV Combined Muon
Electron	Overlap removal Bad cluster removal Electron LooseLH (no requirement related to d_0 , Silicon hits) $ \eta < 2.47$ $p_T > 10.0$ GeV

Table 6.3: Muon and electron requirements applied at analysis level.

6.1.3 Vertex selection

The vertex selection is applied to two-track secondary vertices found in Section 3.4. Secondary vertices with minimum displacement of 2 mm from the primary vertex are selected. The selected displaced vertices are made of two tracks which can be any combination of muon, electron, and non-lepton tracks. Therefore, vertices are separated into three vertex types, control, validation, and signal regions.

In the control region, vertices are required to have two non-leptonic tracks (x^+x^-). In the validation region, vertices are required to have a muon or an electron and another non-leptonic track (μx , ex). In signal region, vertices are required to have a muon pair, an electron pair, or a muon-electron pair ($\mu^+\mu^-$, e^+e^- , $e^\pm\mu^\mp$). The control region and the validation region are used for background (Chapter 8) and systematic uncertainty (Section 9) estimations. The control, validation, and signal regions are summarized in Table 6.4.

Region	Vertex Type
Control	x^+x^-
Validation	$\mu^\pm x^\mp$, $e^\pm x^\mp$
Signal	$\mu^+\mu^-$, e^+e^- , $e^\pm\mu^\mp$

Table 6.4: The control, validation, and signal regions defined by the vertex type.

In all regions, vertices are required to pass a common set of vertex selections described as follows. Vertices are required to have $\chi^2/\text{DOF} < 5$ to reject poorly reconstructed vertices. A minimum transverse displacement of 2 mm from the primary vertex is required to suppress background from prompt decays. Two tracks from a vertex are required to have opposite charges. Vertices are rejected if they are within the volume of disabled Pixel module [51]. Hadronic interaction of charged particles with detector material is a major source of backgrounds. Therefore, the vertices are rejected if they are within dense detector material [52]. The material veto is not applied to $\mu^+\mu^-$ type vertex due to low probability of muon interaction with detector material. Vertices are also required to be in the detector volume covered by the material mapping ($r < 300$ mm, $z < 300$ mm). The vertices are required to have $m > 10$ GeV to suppress backgrounds from low mass SM particles such as J/Ψ . The vertex mass is calculated by the secondary vertex reconstruction algorithm with the assumption that all tracks have pion mass. Cosmic veto is applied to vertices by requiring $R_{\text{CR}} > 0.01$. The cosmic veto is very effective in rejecting cosmic muons reconstructed as back-to-back muon vertices, and the details are discussed in Section 8.1.

In addition to the common vertex selection, at least one electron or muon from the vertex is required to be matched with one of the triggers listed on Table 6.1 and the filters listed on Table 6.2 in the signal region. The vertex selection is summarized in Table 6.5.

Event	GoodRunsList
	Event cleaning
	Trigger filter
	Cosmic veto
	Primary vertex ($z < 200$ mm)
Vertex	Trigger matching (signal region only)
	$\chi^2/\text{DOF} < 5$
	$r > 2$ mm
	Opposite charge
	Disabled module veto
	Material veto (excluding $\mu^+\mu^-$)
	$m > 10$ GeV
	$r < 300$ mm, $z < 300$ mm
	Filter matching (signal region only)

Table 6.5: Event and vertex selections applied to select displaced vertices.

Chapter 7

SIGNAL EFFICIENCY

The signal efficiency of finding displaced dilepton vertex is defined by the ratio of the number of events passing the signal selection (Chapter 6) to the total number of events processed. The signal efficiency can be written as Eq. 7.1.

$$\varepsilon_{\text{overall}} = \varepsilon_{\text{filter}} \cdot \varepsilon_{\text{trigger}} \cdot (\varepsilon_{\text{tracking}} \cdot \varepsilon_{\text{lepton}})^2 \cdot (\varepsilon_{\text{vertexTrack}})^2 \cdot \varepsilon_{\text{vertexFit}}. \quad (7.1)$$

$\varepsilon_{\text{filter}}$ and $\varepsilon_{\text{trigger}}$ together represent the efficiency of RPVLL filter, the ratio of the events passing RPVLL filter to the total events processed. RPVLL filter has the trigger filter as one of its requirements, and because it is desirable to study the trigger efficiency independently from the filter efficiency, RPVLL filter efficiency is factorized into the filter efficiency and the trigger efficiency. $\varepsilon_{\text{tracking}}$ represents the efficiency to reconstruct ID tracks from signal particles, and $\varepsilon_{\text{lepton}}$ represents the efficiency to reconstruct and identify the signal particles as leptons using ID tracks, energy deposite in calorimeters, and MS tracks. $\varepsilon_{\text{vertexTrack}}$ represents the efficiency for the reconstructed signal leptons to be selected for secondary vertex reconstruction, and $\varepsilon_{\text{vertexFit}}$ represents the efficiency to reconstruct a displaced vertex using two signal leptons and pass the vertex selection.

In order to understand the source of signal efficiency loss, the trigger efficiency is studied in Section 7.1, and the tracking and lepton identification efficiencies are studied in Section 7.2. In Section 7.3, the overall reconstruction efficiency of the Z' signal model after the full analysis selection is presented.

7.1 Trigger efficiency

The trigger efficiency is defined as the ratio of the events passing one of the triggers used in this analysis to the total events processed. In this analysis, three triggers listed on Table 6.1 are used to select the events with displaced dilepton vertex candidates. The single muon trigger is sensitive to the events with a $\mu^+\mu^-$ or $e^\pm\mu^\mp$ vertex. The di-photon trigger is mainly used to select the events with an e^+e^- vertex, but a small number of events with an $e^\pm\mu^\mp$ vertex pass this trigger. The single photon trigger is sensitive to the events with e^+e^- or $e^\pm\mu^\mp$ vertex, but its efficiency is relatively low in comparison with the other two triggers.

To illustrate the impact of the trigger efficiencies on the signal samples, the efficiency of each trigger and the combined trigger efficiency is shown in Figure 7.1 using the signal MC samples of Z' decaying to all three channels at $m = 250$ GeV and $c\tau = 250$ mm. The sample with e^+e^- channel shows the highest combined trigger efficiency due to the high efficiency in di-photon trigger, and the sample with $e^\pm\mu^\mp$ channel shows the reduced combined trigger efficiency because $e^\pm\mu^\mp$ vertices have only one track that can satisfy either the single muon or photon trigger.

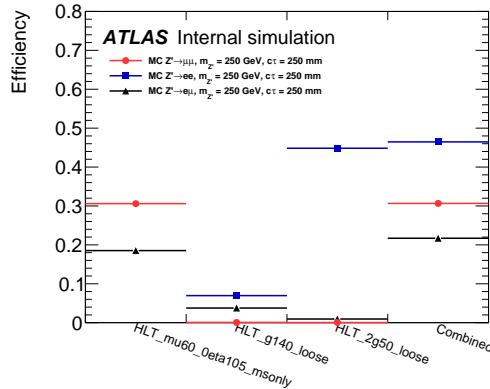


Figure 7.1: Trigger efficiency of single muon, single photon, di-photon, and the combined triggers of the signal MC samples of $Z' \rightarrow \mu^+\mu^-, e^+e^-$, and $e^\pm\mu^\mp$ generated with $m = 250$ GeV and $c\tau = 250$ mm.

The trigger efficiency on all $\mu^+\mu^-$ signal MC samples is shown in Table 7.1. It is evident that at low Z' mass (~ 100 GeV), the combined trigger efficiency on the signal MC sample is significantly reduced because the typical p_T of the signal muons is lower than the p_T threshold of the single muon trigger.

The trigger study indicates that there is a substantial loss in the signal efficiency at trigger level before reconstruction, and developing dedicated, more efficient triggers for long-lived particles will provide potential improvement in sensitivity to long-lived particles. The systematic uncertainties in trigger efficiency is estimated by tag-and-probe method in Section 9.2.

$m_{Z'}$ (GeV)	$c\tau$ (mm)	Single muon	Single photon	Di-photon	Combined
100	100	0.047	< 0.001	0	0.047
100	250	0.043	0	0	0.043
100	500	0.039	0	0	0.039
250	100	0.343	< 0.001	< 0.001	0.344
250	250	0.306	< 0.001	< 0.001	0.307
250	500	0.230	< 0.001	< 0.001	0.230
500	100	0.454	0.010	< 0.001	0.459
500	250	0.410	0.009	< 0.001	0.415
500	500	0.331	0.008	0.001	0.336
750	100	0.541	0.026	0.002	0.553
750	250	0.470	0.023	0.003	0.481
750	500	0.391	0.022	0.001	0.402
1000	100	0.570	0.039	0.004	0.586
1000	250	0.512	0.036	0.003	0.526
1000	500	0.430	0.034	0.004	0.444

Table 7.1: Trigger efficiency of single muon, single photon, di-photon triggers, and the combined trigger efficiency on the signal MC samples of $Z' \rightarrow \mu^+\mu^-$.

7.2 Lepton reconstruction efficiency

The tracking efficiency, $\varepsilon_{\text{track}}$, and the lepton identification efficiency, $\varepsilon_{\text{lepton}}$, are studied together as a lepton reconstruction efficiency. The lepton reconstruction efficiency is defined and estimated as follows. From a signal MC sample, the leptons decaying from Z' are collected at generator-level, referred as *truth* signal leptons. For each truth signal lepton, if there is a reconstructed lepton with its ID track matched to the ID track of the truth signal lepton by a hit-based truth matching scheme, it is marked as reconstructed. The ratio of reconstructed signal leptons to the total number of signal leptons produced in the sample is taken as the lepton reconstruction efficiency. No RPVLL or trigger filter is applied in estimating the lepton reconstruction efficiency.

Figure 7.2 shows the representative plot of the lepton reconstruction efficiency as a

function of track parameters using the combined signal MC samples of Z' decaying to all three channels, generated with $m = 250$ GeV and $c\tau = 250$ mm.

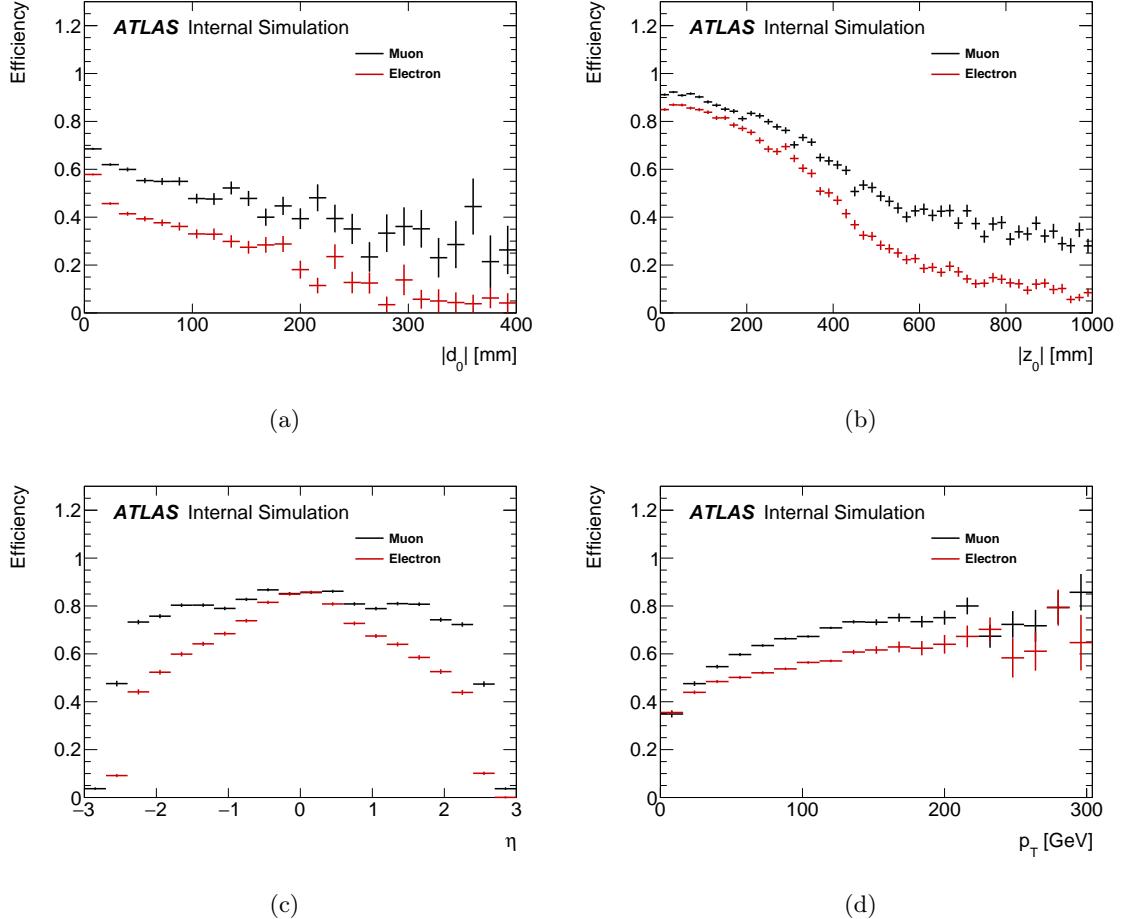


Figure 7.2: Lepton reconstruction efficiency as a function of (a) d_0 , (b) z_0 , (c) η , and (d) p_T of signal leptons using the signal MC sample generated with $m = 250$ GeV and $c\tau = 250$ mm.

It is evident that the efficiency drops drastically at $\eta > 2.0$ where the Pixel barrel region ends due to the minimum silicon hits requirement on tracks as shown in Table 3.1. The efficiency is not very sensitive to p_T except low p_T region ($p_T < 20$).

The lepton reconstruction efficiency decreases for large d_0 and z_0 . In the signal MC samples, most of Z' decay within the Pixel barrel region, $r < 122.5$ mm and $z < 400.5$ mm, where the lepton reconstruction efficiency is high.

7.3 Overall reconstruction efficiency

The overall reconstruction efficiency is defined as the ratio of Z' 's reconstructed as displaced vertices in the signal region to the total Z' produced in the sample. In this section, representative plots of event cut flow, vertex cut flow (Section 7.3.1), and overall reconstruction efficiency distributions (Section 7.3.2) are presented using the signal MC samples generated with $m = 500, 1000$ GeV, and $c\tau = 100$ mm.

7.3.1 Event and vertex cut flow

The MC samples are processed with steps described in Section 6.1. The analysis-level cuts, the event and the vertex selections described in Table 6.5, are applied to the processed samples. Representative plots of the event cut flow and the vertex cut flow are shown in Figure 7.3 using the signal MC samples of Z' decaying to $\mu^+\mu^-$ generated with $m = 500, 1000$ GeV for $c\tau = 100$ mm.

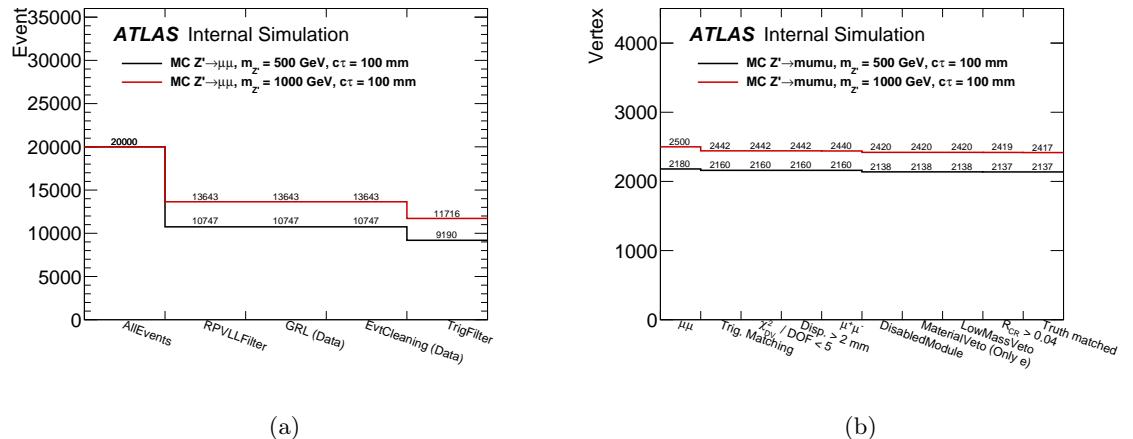


Figure 7.3: (a) Event cut flow, and (b) vertex cut flow using the signal MC samples of $Z' \rightarrow \mu^+\mu^-$ generated with $m = 500, 1000$ GeV for $c\tau = 100$ mm.

In the event cut flow, RPVLL filter is applied during the sample processing. GoodRunsList filter and Event cleaning are shown as place holders as they are only applied to data sample.

In the vertex cut flow, displaced vertices are reconstructed in about $\sim 25\%$ of the signal events passing the event selection, indicating that there is a significant loss of signal efficiency in the reconstruction process. The following selection criteria, $\chi^2 / \text{DOF} < 5$ and the

minimum displacement cut ($r > 2$ mm), are applied, but the effect is expected to be very small as the same requirements are applied in the secondary vertex reconstruction algorithm. Material veto is applied to all vertex types except $\mu^+\mu^-$ vertex. The minimum dilepton mass requirement and cosmic veto cuts have minimum impact on the signal efficiency.

7.3.2 Efficiency distribution

The overall reconstruction efficiency is studied by examining the efficiency distributions in the transverse (r), longitudinal (z) vertex position, and the angular distributions of the reconstructed vertices. The representative efficiency distributions are shown in Figure 7.4 using the signal MC samples generated with $m = 500, 1000$ GeV for $c\tau = 100$ mm.

The overall efficiency shows a significant dependence on vertex position which decreases at large r and z due to the minimum silicon hits requirement on tracks. The first bins in r and z distributions have lower efficiency due to the minimum displacement requirement ($r > 2$ mm) on secondary vertices. The r distribution shows features that reflects the physical structure of the ID. The η distribution has higher efficiency in the central region, and the ϕ distribution is uniform as expected.

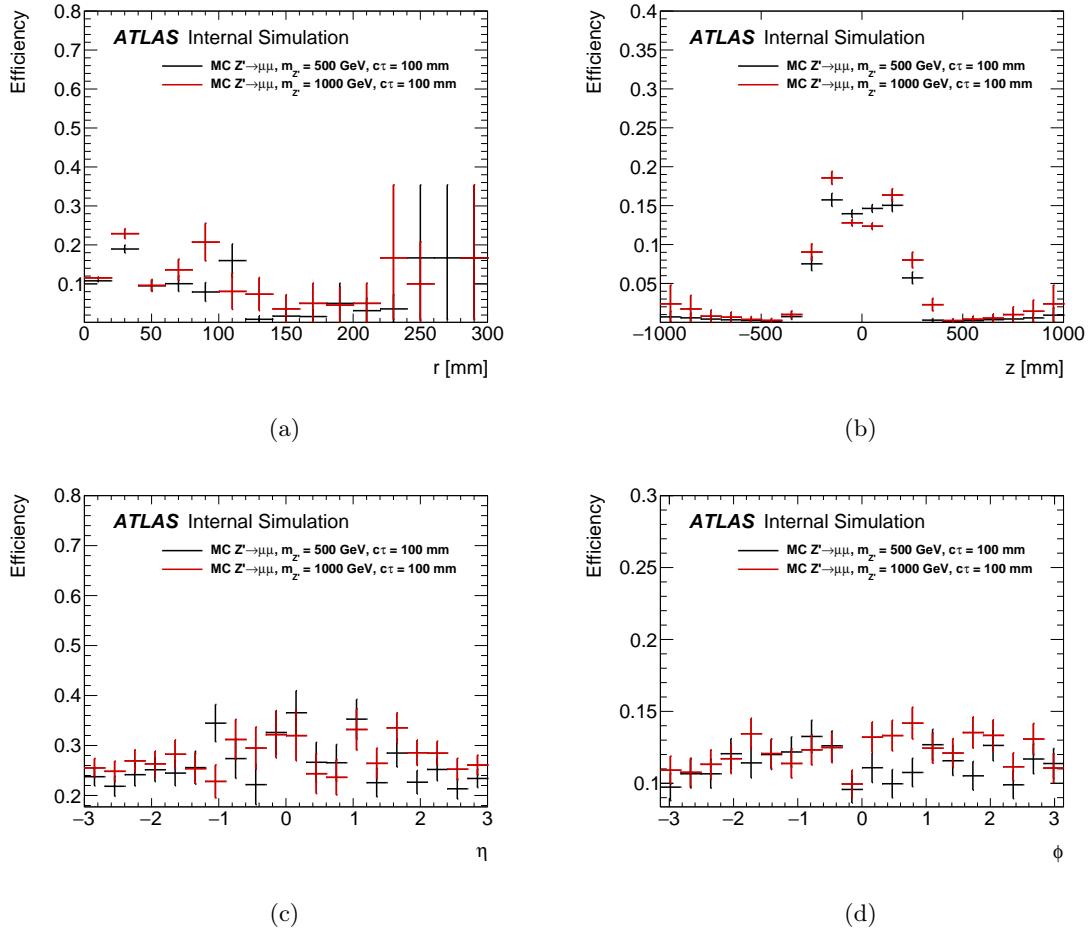


Figure 7.4: Overall efficiency distributions in (a) r , (b) z , (c) η , and (d) ϕ of the signal MC samples of $Z' \rightarrow \mu^+\mu^-$ with $m = 500, 100$ GeV for $c\tau = 100$ mm.

Chapter 8

BACKGROUND ESTIMATION

Due to the lifetime ($c\tau > 2$ mm) and mass ($m > 10$ GeV) requirements applied at vertex selection, no SM background is expected in the signal region in search for displaced dilepton resonance. Therefore, two non-collision backgrounds are considered in this search: cosmic background and *random-crossing* background. The cosmic background is the dominant background in this analysis and is estimated In Section 8.1. In Section 8.2, background from random-crossing of two uncorrelated tracks are estimated.

8.1 Cosmic Background

A cosmic muon passing through the ID during a collision event can be reconstructed as a back-to-back muon pair with opposite electric charges, and the pair can be reconstructed as a displaced $\mu^+\mu^-$ vertex passing all signal selection criteria in this analysis. $\mu^+\mu^-$ vertex.

This cosmic background is suppressed by implementing the cosmic veto, $R_{\text{CR}} < 0.01$ (Section 6.1.1). The event cut flow in Figure 7.3a shows that the cosmic veto is very effective in signal selection, i.e., the signal efficiency loss due to the cosmic veto is negligible. To illustrate the R_{CR} distribution of cosmic muons, a cosmic control region is defined as follows:

- Events are required to fail the cosmic veto.
- Events are required to have at least two muons satisfying vertex track selection (Table 3.3).
- All other event selections are kept the same as the signal region.

In this control region, pairs of two muons with leading p_T are studied using the data

sample. Figure 8.1 shows the distribution of the pairs in $|\Delta\phi|$ and $\Sigma\eta$. The distribution shows that a significant fraction of muons pairs is from cosmic rays and is constraint in small R_{CR} region.

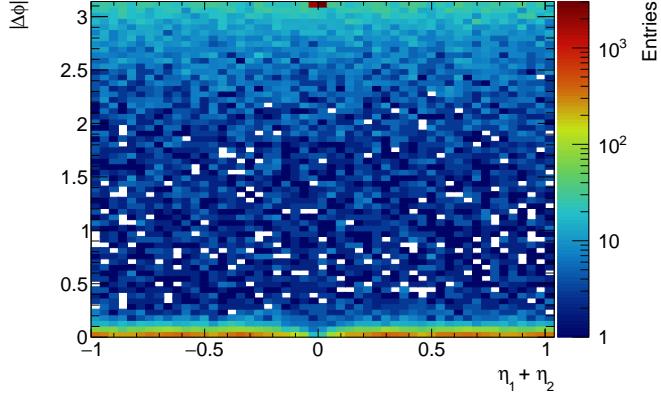


Figure 8.1: Distribution of pairs of two muons with leading p_T in $|\Delta\phi|$ and $\Sigma\eta$ found in the cosmic control region using the data sample. The sharp peak at $|\Delta\phi| = \pi$ and $\Sigma\eta = 0$ shows that a significant fraction of muon pairs in the region is from cosmic muons.

To estimate the cosmic background in the signal region, the distributions of $\mu^+\mu^-$ vertices and pairs from the data sample in small R_{CR} region are shown in Figure 8.2. There are 246 $\mu^+\mu^-$ vertices found in the data sample that pass all of the signal selection except the cosmic veto, and the distribution vanishes around $R_{\text{CR}} = 0.004\mu^+\mu^-$, suggesting that the cosmic background is effectively suppressed by the cosmic veto cut of $R_{\text{CR}} = 0.01$.

For more accurate estimation of the background, the $\mu^+\mu^-$ pair distribution is normalized to the $\mu^+\mu^-$ vertex distribution as shown in Figure 8.2b, and the normalized distribution is extrapolated to the signal region. With this method, the cosmic background is estimated to be 0.27 ± 0.14 (stat.). This background is about two orders of magnitude larger than the random crossing background. Therefore, the cosmic muon background is the dominant source of background for this analysis.

8.2 Random-Crossing Background

The random-crossing of two uncorrelated tracks can be a major source of the backgrounds in the search for displaced dilepton vertices. This background is expected to increase with

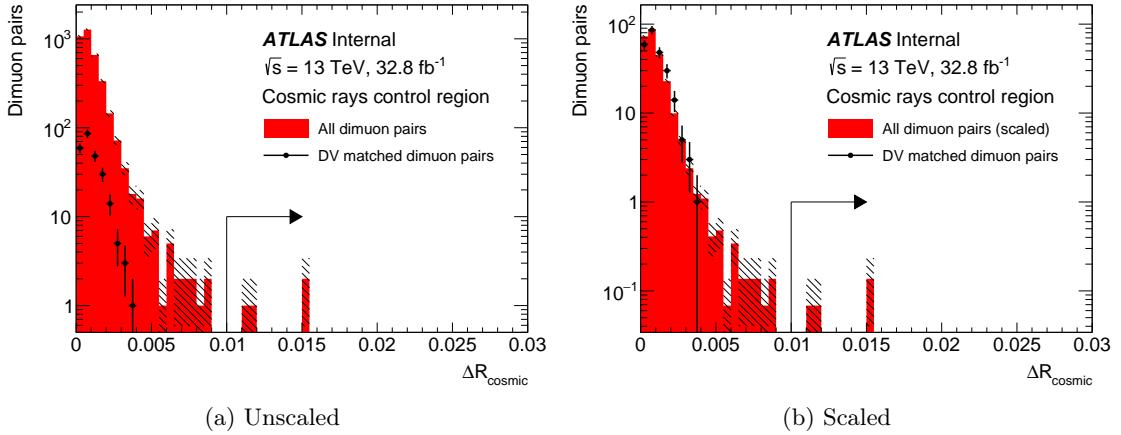


Figure 8.2: (a) Distribution of $\mu^+\mu^-$ vertices and pairs from the data sample in small R_{CR} region. The red distribution represents all $\mu^+\mu^-$ pairs. The black dots represent the subset of pairs forming a $\mu^+\mu^-$ vertex. The same distribution is shown in (b) with $\mu^+\mu^-$ pairs normalized to $\mu^+\mu^-$ vertices.

more pile up in Run 2.

This random-crossing background is estimated by a data-driven method called the *track flipping* (TF). In this method, secondary vertex reconstruction is performed on each pair of tracks from all possible combinations of tracks after one random track from each pair is flipped with respect to the beam spot. Because one track is flipped in each pair of tracks, the resulting vertices provide good estimation for random-crossing background. In addition, another random-crossing background method called the *Event mixing* is used to estimate systematic uncertainty in the background estimation.

The TF and event mixing methods are described in Section 8.2.1 and 8.2.2, respectively. In Section 8.2.3, the TF method is tested on the background MC samples, and the result is compared with the corresponding result from the event mixing. In Section 8.2.4, the random-crossing background in data is estimated by the TF method, and its systematic uncertainty is estimated by comparing the estimation from the TF and event mixing in Section 8.2.5.

8.2.1 Track flipping method

In the TF method, events are selected by the same requirement described in Section 6.1. From the selected events, ID tracks associated with a muon, electron, or neither, referred as muon, electron, or non-leptonic track, respectively, are selected with the track criteria

(Table 3.3) used for the secondary vertexing algorithm. Lepton tracks are required to pass the same selection criteria described in Table 6.3. Non-leptonic tracks are required to pass the minimal kinematic selection ($p_T > 10$ GeV, $\eta < 2.5$) to match with the kinematic selection for leptons.

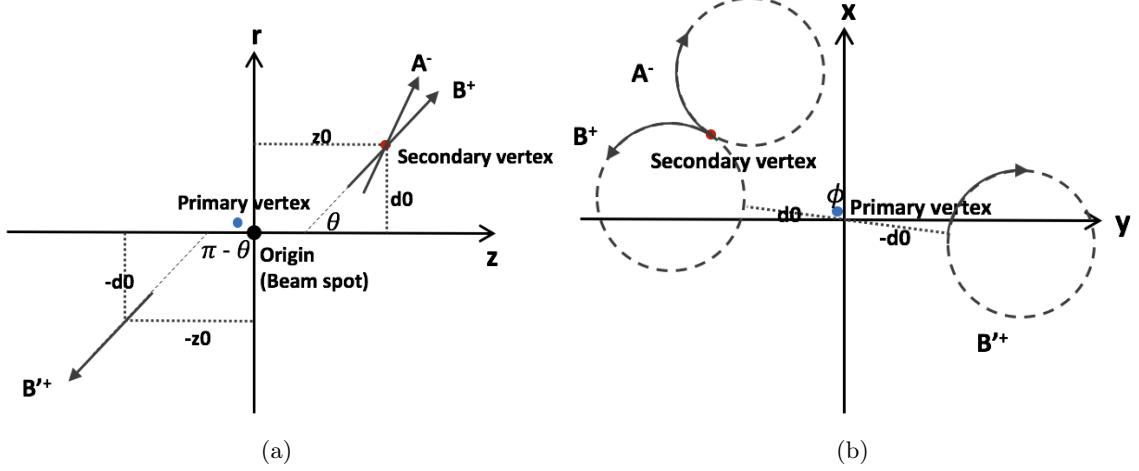


Figure 8.3: Description of track flipping method in (a) $r - z$ and (b) $x - y$ plane. Given two tracks A and B originating from a common secondary vertex, one random track is flipped with respect to the beam spot and is denoted as B' . The resulting flipped track pair, AB' , cannot form a vertex due to the separation in space.

From the selected tracks, track pairs are created from all possible combination of muon, electron, or non-leptonic tracks which fall into one of the six categories, $\mu^+ \mu^-$, $e^+ e^-$, $e^\pm \mu^\mp$, $e^\pm x^\mp$, $\mu^\pm x^\mp$, or $x^+ x^-$ track pair, where x represents a non-leptonic track. For each pair of tracks, one random track is flipped with respect to the beam spot ($d_0 \rightarrow -d_0$, $z_0 \rightarrow -z_0$, $\phi \rightarrow \phi + \pi$, $\theta \rightarrow \pi - \theta$), creating a *flipped track pair*. The secondary vertex algorithm used in the reconstruction of data or MC sample is used to reconstruct displaced vertices using these flipped track pairs. Vertex selection cuts similar to the cuts listed in Table 3.3 are applied to the vertices found from flipped track pairs. The only differences in the vertex cuts are:

- Trigger matching is only required for $\mu^+ \mu^-$, $e^+ e^-$, and $e^\pm \mu^\mp$ vertices because non-leptonic tracks cannot be matched to lepton triggers,
- Filter matching is only required for $\mu^+ \mu^-$, $e^+ e^-$, and $e^\pm \mu^\mp$ vertices for the same reason.

The resulting vertices, referred as *track-flipping vertices*, fall into one of the same six categories as track pairs. Because one random track is flipped, track-flipping vertices are purely from random-crossing of tracks as depicted in Figure 8.3. Therefore, track-flipping vertex yields provide a good estimation for random-crossing background of each type. Also, because trigger and filter matchings are not required in the control and validation region, the TF method provides conservative background estimation.

8.2.2 Event mixing method

The event mixing method is similar to the TF, but instead of flipping a track from pair of tracks, it combines tracks from different events to create uncorrelated track pairs, i.e., two tracks are not originating from a real vertex.

The event mixing method proceed as follows. First, muon, electron, and non-leptonic tracks that satisfy the track criteria (Table 3.3) are collected from all events, resulting in a collection of all potential seed objects in the sample. Lepton tracks are required to pass the same selection criteria⁴ described in Table 6.3. Non-leptonic tracks are required to pass the minimal kinematic selection ($p_T > 10$ GeV, $\eta < 2.5$) to match with the kinematic selection for leptons.

Pairs of tracks are randomly sampled from the collection. For each track pair, a primary vertex is randomly chosen from all events with a lepton candidate. Primary vertices are required to evaluate the displacement cut and quality requirements of the vertexing algorithm. The secondary vertex reconstruction is performed on each track pair and the associated primary vertex to reconstruct displaced vertices, referred as *event-mixing vertices*.

The ratio of event-mixing vertex yields to the number of track pairs sampled represents the probability, p_{xing} , of two tracks forming a displaced vertex by a random chance. Using p_{xing} and the total number of track pairs of each type ($\mu^+\mu^-$, e^+e^- , $e^\pm\mu^\mp$, $\mu^\pm x^\mp$, $e^\pm x^\mp$, x^+x^-) in data, the random-crossing background is estimated for each type by, e.g.,

$$N_{\mu^+\mu^-} = T_{\mu^+\mu^-} \times p_{\text{xing}}, \quad (8.1)$$

where $N_{\mu^+\mu^-}$ represent the estimated random-crossing background of $\mu^+\mu^-$ type, and $T_{\mu^+\mu^-}$ represents the total number of $\mu^+\mu^-$ pairs present in data. The random-crossing probability, p_{xing} , is estimated individually for each type of vertices. The details on this method can be found in [LINK TO INTERNAL NOTE].

⁴Only lepton pairs with an invariant mass greater than 6 GeV are used in the normalization procedure to remove any contamination from low mass processes.

8.2.3 MC study

The TF method is tested using the background MC sample described in Section 5.2.2, and the resulting vertex yields and distributions are compared with the corresponding result from event mixing method. A representative plot of vertex cut flows in the TF method is shown in Figure 8.4 using track-flipping x^+x^- vertices from the background MC samples.

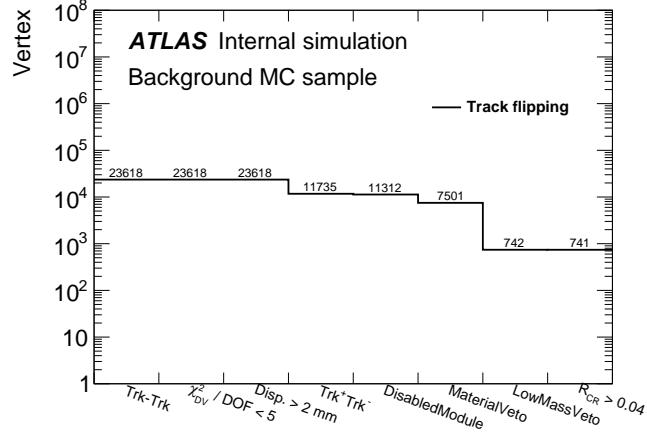


Figure 8.4: Vertex cut flow applied on x^+x^- vertices from the TF method.

The vertex yields from the TF and event mixing method, which represent the estimation for random-crossing background, are compared with the vertex yields from reconstruction in Table 8.1. No random-crossing background of $\mu^+\mu^-$, e^+e^- , or $e^\pm\mu^\mp$ type is expected from the MC samples using both methods.

Vertex Type	Track Flipping	Event Mixing	Background MC Samples
$\mu^\pm x^\mp$	1	1.3	0
$e^\pm x^\mp$	0	0.3	0
x^+x^-	741	714.0	676

Table 8.1: Comparison of the number of $\mu^\pm x^\mp$, $e^\pm x^\mp$, and x^+x^- vertices found in the track flipping, estimated from the event mixing, and reconstructed in the background MC samples.

The x^+x^- vertex yields from the track flipping and the event mixing methods agree within

the statistical uncertainty. The x^+x^- vertex distributions of the vertices from the track flipping, event mixing, and from reconstruction are shown in Figure 8.5. The distributions of the track flipping and the event mixing agree reasonably well with the distributions of vertices found from the reconstruction.

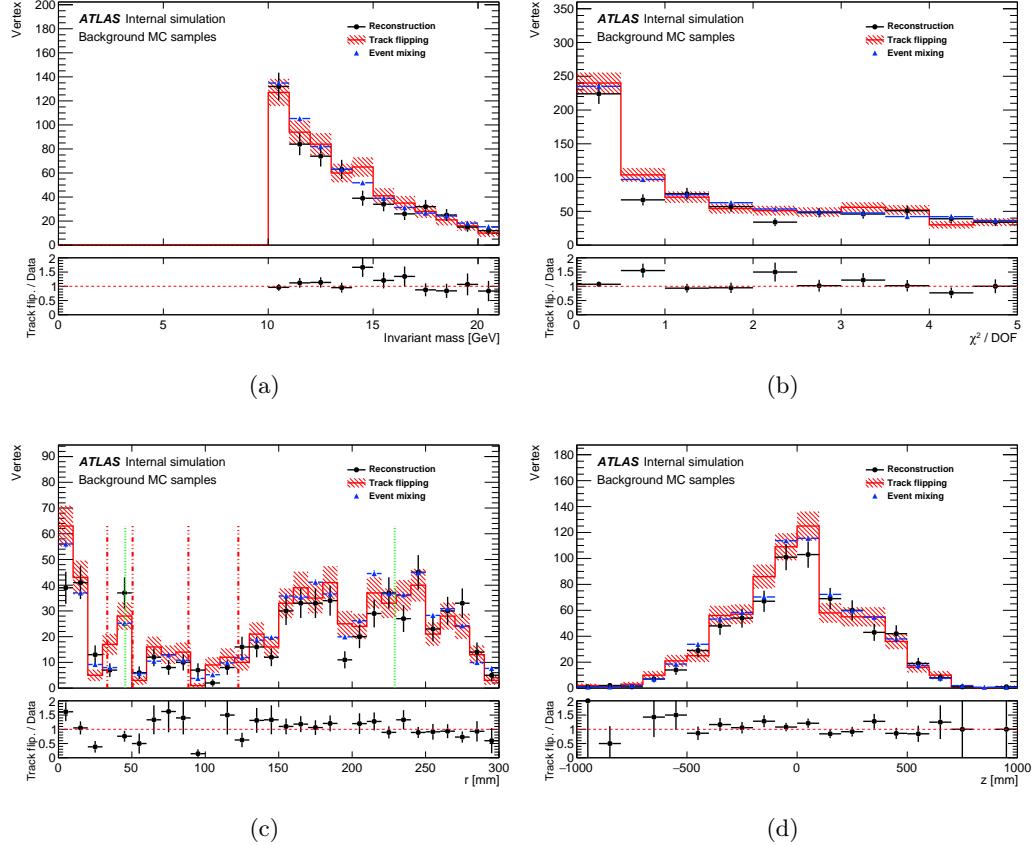


Figure 8.5: Comparison of of (a) vertex mass, (b) χ^2/DOF , (c) transverse, and (d) longitudinal position of x^+x^- vertices reconstructed, found from the track flipping, and estimated using the event mixing. In (c), the red dashed lines indicate the four Pixel layers and the first layer of SCT. The green dotted lines indicate the Inner Support Tube (45.5 mm) and Pixel Support Tube (229 mm).

8.2.4 Estimating random-crossing background with data sample

Random-crossing background is estimated by performing the TF method on the data sample. Following the procedure described in Section 8.2.1, track-flipping vertices are created, and

the vertex yields in the control and validation regions are used to make an estimation in the signal region.

Vertex distribution in control region In the control region, the x^+x^- vertices found from the track flipping method are compared to the vertices reconstructed in the data sample in Figure 8.6. The distributions shows that the TF method reproduces the data reasonably well including some of the structures of the ID, suggesting that the TF method provides a reasonable estimation of the random-crossing background.

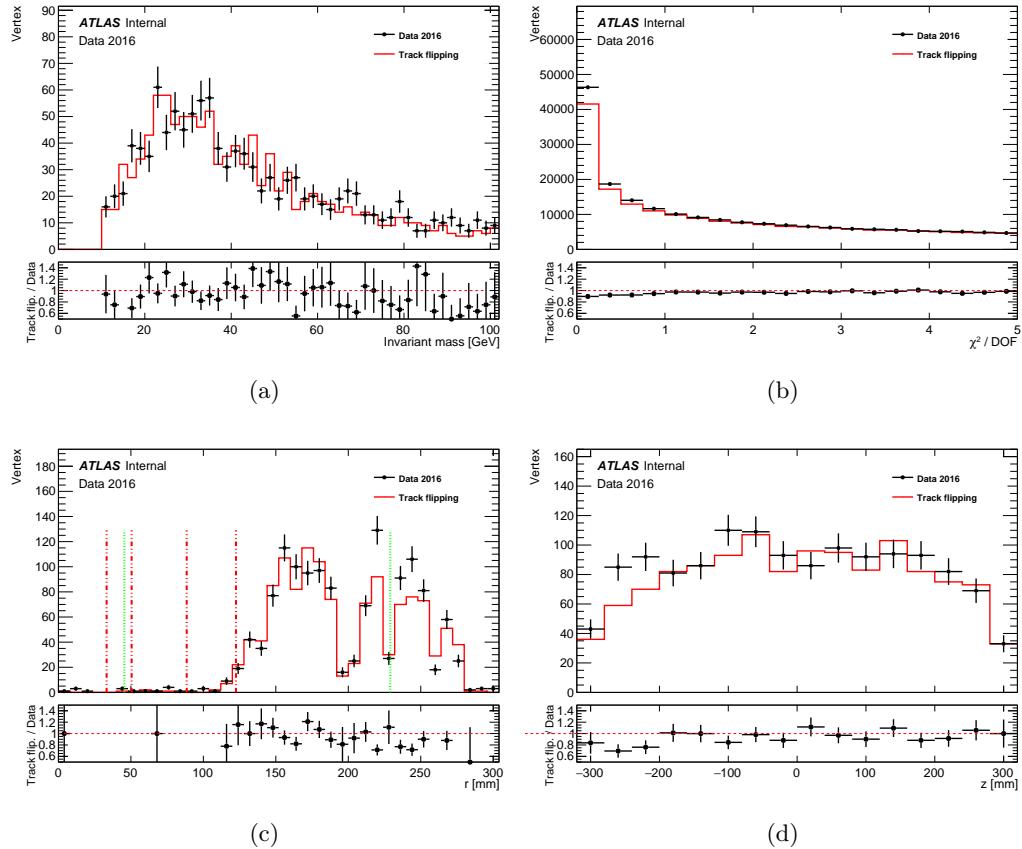


Figure 8.6: Comparison of (a) vertex mass, (b) χ^2/DOF , (c) transverse, and (d) longitudinal position of vertices found from reconstruction with the track-flipping vertices in the control region of the data sample. In (c), the red dashed lines indicate the four Pixel layers and the first layer of SCT. The green dotted lines indicate the Inner Support Tube (45.5 mm) and Pixel Support Tube (229 mm).

However, because of the limited statistics in lepton pairs in the data sample, the track-flipping vertex yields in the signal region cannot be directly used as random-crossing back-

ground estimation. Instead, the track-flipping vertex yields in the control region and validation region are extrapolated to estimate random-crossing background in the signal region using lepton probability, defined as follows:

- $P(e)$ is defined as the ratio of electrons to inner detector tracks in the entire sample,
- $P(\mu)$ is defined as the ratio of muons to inner detector tracks in the entire sample,

where track requirements described in Table 3.3 is required to both leptons and inner detector tracks.

Extrapolation from control region The track-flipping vertex yields in the control region is extrapolated using Eq. 3 to the validation regions to estimate the vertex yields, representing random-crossing background estimation in the validation region. The estimated $\mu^\pm x^\mp$ and $e^\pm x^\mp$ vertex yields are compared with the observed track-flipping vertex yield in the region. The ratio of the observed track-flipping vertex to the extrapolated vertex in the validation region is used as scale factors for the estimation in the signal region,

$$S_{xx \rightarrow \mu x} = \frac{N_{\mu x}^{obs}}{N_{\mu x}^{est}},$$

$$S_{xx \rightarrow e^\pm x^\mp} = \frac{N_{ex}^{obs}}{N_{ex}^{est}} \quad (8.2)$$

where $N_{\mu x}^{obs}$ and $N_{\mu x}^{est}$ (N_{ex}^{obs} and N_{ex}^{est}) represent the number of observed track-flipping vertex and the estimated vertex of each type.

The track-flipping vertex yield is then extrapolated to the signal region using Eq. 3 to estimate random-crossing background, and the scale factors defined by Eq. 5 are applied to the extrapolation for more accurate estimation of the background.

Extrapolation from validation region Similarly, the track-flipping vertex yields in the validation region is extrapolated to the signal to estimate vertex yields using Eq. 4, and the scale factors defined by Eq. 5 are applied to the extrapolation to obtain the background estimation.

The lepton probability, track-flipping and reconstructed vertex yields in the control and validation region, the scale factors, and the estimated random-crossing background are summarized in Table 8.2.

8.2.5 Systematic uncertainty in random-crossing background

	Tracks	$p(\ell)$		Tracks-flipping	Data	Type	SF	
x	2.47×10^7	-		xx	1255	1346	$S_{xx \rightarrow \mu x}$	0.82
μ	5.23×10^4	2.10×10^{-3}		μx	3	4	$S_{xx \rightarrow ex}$	0.19
e	3.63×10^4	1.46×10^{-3}		ex	1	0		
Sum	2.48×10^7	-					(c) Scale factors	

(a) Lepton probability

	Estimation	Applying SF		Estimation	Applying SF
$N_{\mu x}$	4	-		$N_{\mu\mu}$	2.19×10^{-3}
N_{ex}	5	-		N_{ee}	1.05×10^{-3}
$N_{\mu\mu}$	2.69×10^{-3}	1.79×10^{-3}		$N_{e\mu}$	3.89×10^{-3}
N_{ee}	5.56×10^{-3}	1.99×10^{-4}			1.96×10^{-3}
$N_{e\mu}$	7.73×10^{-3}	1.96×10^{-3}			

(d) Extrapolation from control region

(b) Vertex yields in the control and validation region

(e) Extrapolation from validation region

Table 8.2: Random-crossing background estimation in data by the TF method

Chapter 9

SYSTEMATIC UNCERTAINTIES

The systematic uncertainty in the signal efficiency is estimated by estimating the systematic uncertainty of each efficiency factor in Eq. 7.1.

The systematic uncertainties in $\varepsilon_{\text{track}}$, $\varepsilon_{\text{vertexTrack}}$, and $\varepsilon_{\text{vertexFit}}$ are studied using K_S in Section 9.1. The systematic uncertainties in $\varepsilon_{\text{trigger}}$ is studied in Section 9.2 using tag-and-probe method with $Z \rightarrow e^+e^-,\mu^+\mu^-$ events.

9.1 Systematic Uncertainties in Tracking and Vertexing Efficiency

The systematic uncertainties in $\varepsilon_{\text{track}}$, $\varepsilon_{\text{vertexTrack}}$, and $\varepsilon_{\text{vertexFit}}$ are estimated by comparing the tracking and vertexing efficiencies between the data and the background MC samples described in Section 5.1 using the process, $K_S \rightarrow \pi^+\pi^-$. In order to understand the validity and the limitation of this method, the kinematic distributions of K_S and Z' found in this method are compared in Appendix C.

Events are selected using the same event selection described in Section 6.1. From the selected events, K_S candidates, referred as K_S vertices, are selected by applying K_S vertex selection to the secondary vertices in the events. K_S vertex selection is similar to the Z' signal vertex selection, but for the consistency with K_S study in Run I and further background reduction, additional vertex cuts as described in Ref. [53] are applied in K_S vertex selection. The mass window of 0.35 to 0.65 GeV is used in the K_S vertex selection. The difference between K_S and Z' vertex selections are summarized in Table 9.1. Figure 9.1 shows K_S vertex cut flow in the data and the background MC samples.

After applying the event and K_S vertex selection, the K_S vertex distributions in the

	Z'	K_S
Vertex type	$\mu^+\mu^-$, $e^\pm\mu^\mp$, e^+e^-	x^+x^-
Mass (GeV)	> 10.0	$[0.35, 0.65]$
Additional cut	-	K_S selection [53]

Table 9.1: Comparison of Z' and K_S vertex selections.

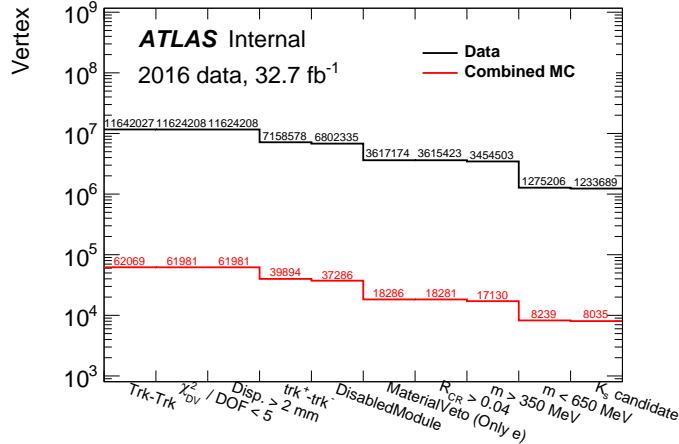


Figure 9.1: Vertex cut flow applied on K_S vertices in the data and MC samples

data are compared to the MC samples in Figure 9.2. The data sample is normalized to the MC sample which has limited statistics. There are good agreements in the invariant mass, p_T , transverse, longitudinal position, and decay length of the vertices, except the pile-up distribution as expected.

K_S vertices found in the data and MC samples are binned in decay radius, r , and the K_S yields in each bin are estimated from a fit using Breit-wigner. Figure 9.3 shows a few representative K_S mass distributions (others are included in Appendix B). Background is negligible and hence not included in the fit. The estimated K_S yields are normalized to the number of K_S found in the lowest r bin since the expected number of K_S in the data samples is unknown.

The K_S yield, normalized to the yield with $r < 20$ mm, is compared to the MC in Figure 9.4. The lower pane shows the double ratio,

$$\frac{N_R^{\text{data}}}{N_{R_0}^{\text{data}}} \Big/ \frac{N_R^{\text{MC}}}{N_{R_0}^{\text{MC}}} \quad (9.1)$$

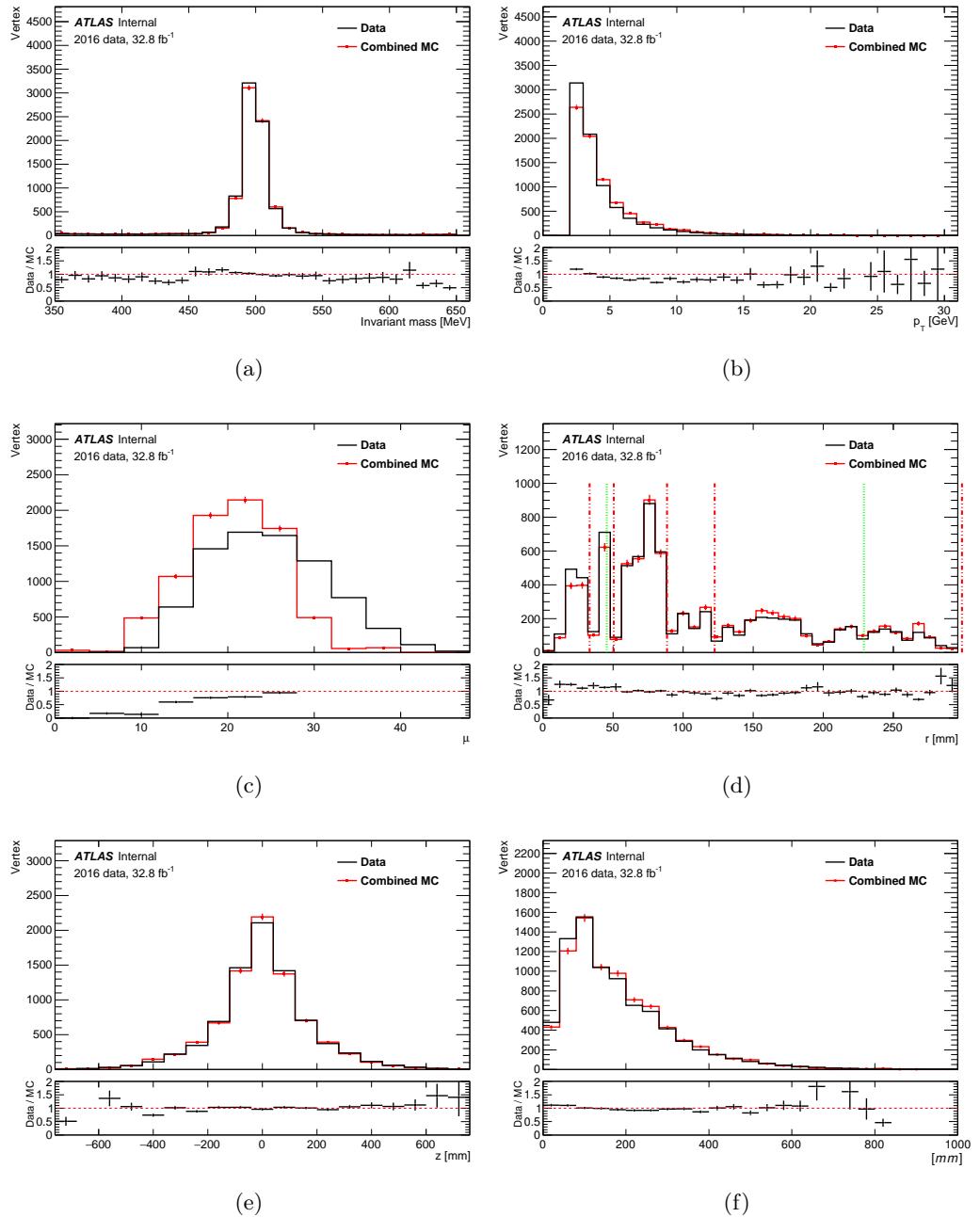


Figure 9.2: Comparison of the (a) invariant mass, (b) p_T , (c) μ , (d) transverse, (e) longitudinal position, and (f) decay length of K_S in the data with the MC samples. Data is normalized to MC. In (d), the red dashed lines indicate the four Pixel layers and the first layer of SCT. The green dotted lines indicate the Inner Support Tube (45.5 mm) and Pixel Support Tube (229 mm).

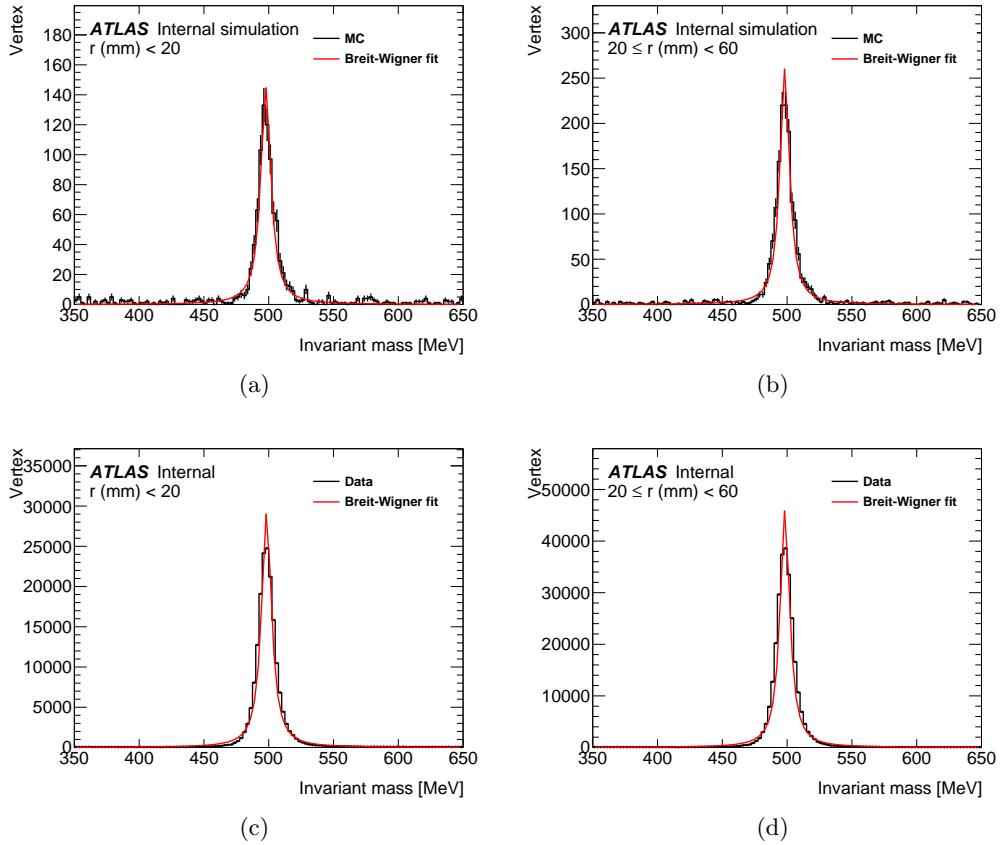


Figure 9.3: Representative distributions of the K_S invariant mass for (a) $r < 20$ mm, and (b) $20 < r < 60$ mm in the background MC sample. The corresponding plots from the data sample are shown in (c) and (d). The mass distributions are fitted with a Breit-Wigner.

which shows deviation from unity with increase of r . The difference in yield is then convoluted with the r distribution of Z' to estimate the systematic uncertainty in tracking and vertexing.

9.2 Systematic uncertainties in trigger efficiency

Systematic uncertainties in lepton triggers are usually measured with tag-and-probe studies on $Z + \text{jet}$ where most leptons have small impact parameters. However, because the leptons originating from displaced vertices tend to have large impact parameters, the standard systematics on triggers provided by the performance groups cannot be applied. In the following, the systematic uncertainties in the lepton triggers are estimated using tag-and-probe method on the data and $Z + \text{jets}$ MC samples.

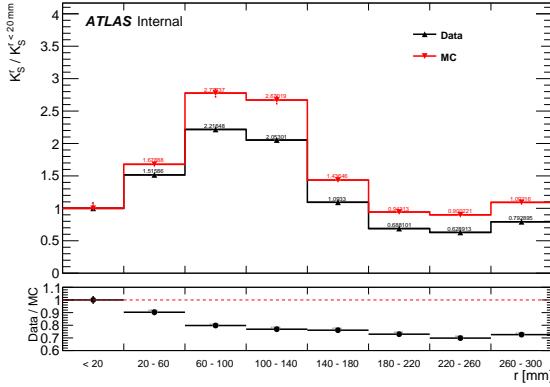


Figure 9.4: The radial distribution of K_S yield, normalized to the lowest r bin in the data and MC samples. The lower pane shows the double ratio as defined in the text.

The estimated systematic uncertainties are valid only if the trigger efficiencies do not depend on impact parameters or if this dependence is modelled reasonable well in simulations. Therefore, the efficiencies of the single photon and single muon triggers listed on Table 6.1 are estimated using the signal MC samples and shown in Figure 9.5.

The photon trigger efficiency is consistent for both the transverse and the longitudinal impact parameter. The muon trigger efficiency starts to decrease for large impact parameters, $|d_0| \approx 120$ mm and $|z_0| \approx 200$ mm. However, the decreasing muon efficiency at very large impact parameters is neglected since the fraction of reconstructed muons with such large impact parameters is less than 10% at the lifetime of $c\tau = 100$ mm.

9.2.1 Photon triggers

The systematic uncertainties of the single photon and the di-photon triggers are estimated with a standard tag and probe method on $Z \rightarrow ee$ events both in data and MC samples. The di-photon trigger (`HLT_2g50_loose`) is studied using the single muon trigger (`HLT_g50_loose`) with the same p_T threshold. The selection criteria of electron tag-and-probe candidates are listed in Table 9.2. In addition, pairs are required to have opposite signs and to satisfy the mass requirement ($|m_{e^+e^-} - m_Z| < 10$ GeV) and the isolation requirement of $\Delta R(\text{tag}, \text{probe}) > 0.4$.

The invariant mass distributions of the tag-and-probe pairs found in the data and MC samples are shown in Figure 9.6. The shape of distribution is in good agreement with negligible background for both triggers. Therefore, no background subtraction is performed

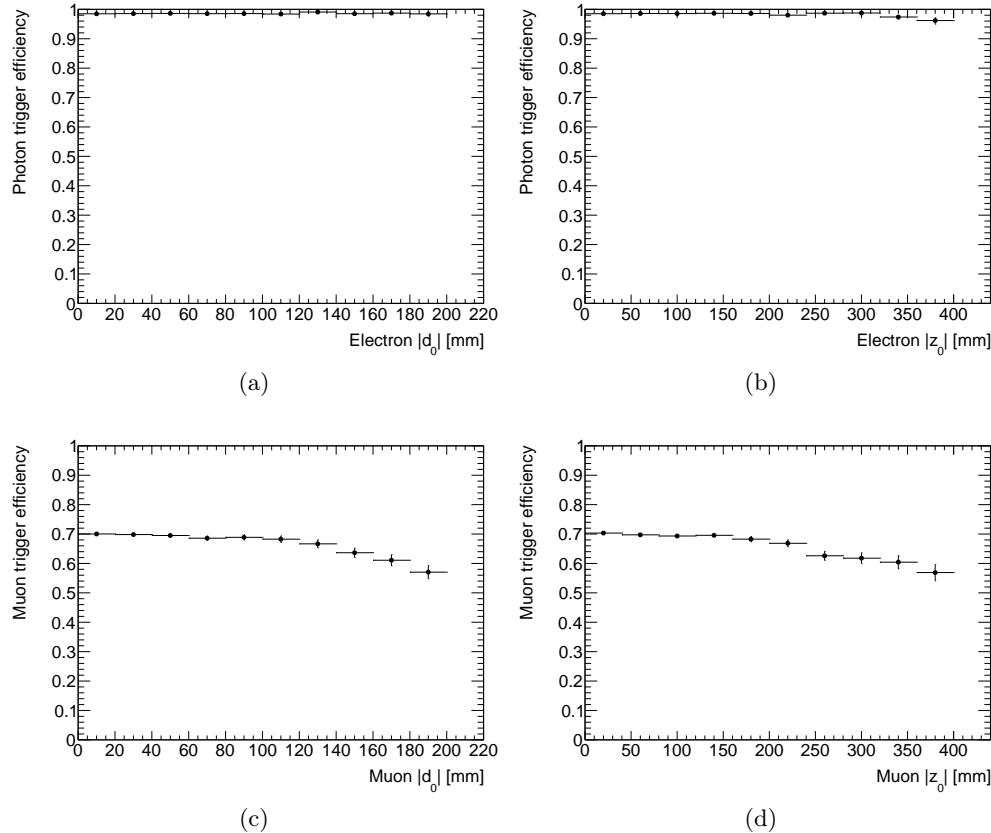


Figure 9.5: The efficiency of the single photon trigger in electron (a) $|d_0|$ and (b) $|z_0|$. The corresponding plots of the single muon trigger are shown in (c) and (d).

Selection	Tag	Probe
p_T (GeV) >	27	30
Trigger matched	HLT_e26_lhtight_nod0_ivarloose	—
$ \eta $	< 1.37 or (> 1.52 and < 2.47)	< 2.47
Identification	TightLH	LooseLHNoD0
Object quality	yes	yes
Track isolation	yes	—
Jet veto	—	yes

Table 9.2: Selection criteria for tag-and-probe electrons in $Z+jets$ studies.

in the calculation of the trigger efficiencies,

$$\epsilon_{\text{trigger}} = \frac{\text{Number of probes matched to trigger}}{\text{Number of all probes}}. \quad (9.2)$$

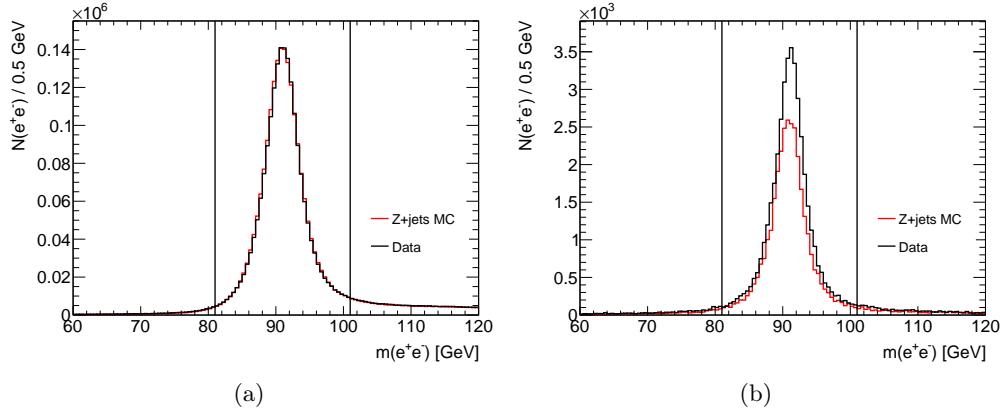


Figure 9.6: Invariant mass distributions of the tag-and-probe electron pairs used to study the efficiencies of the (a) `HLT_g50_loose` and (b) `HLT_g140_loose` trigger in the data and $Z+jets$ MC samples. Only the pairs with a probe electron in the plateau region of Figure 9.7a and 9.7b are considered.

The selected tag-and-probe electrons are used to estimate the efficiencies of photon triggers, shown as a function of probe p_T , η , and $|z_0|$ in Figure 9.7. The efficiencies in p_T show that the `HLT_g50_loose` plateau starts at 55GeV, and `HLT_g140_loose` plateau starts at 148GeV. The efficiencies in η show good agreement between data and MC for electrons reconstructed inside the barrel, whereas small discrepancy in efficiencies are shown for electrons at the boundary regions and in the end-cap regions. Also, the efficiency in $|z_0|$

shows no dependence of the photon trigger efficiencies on $|z_0|$

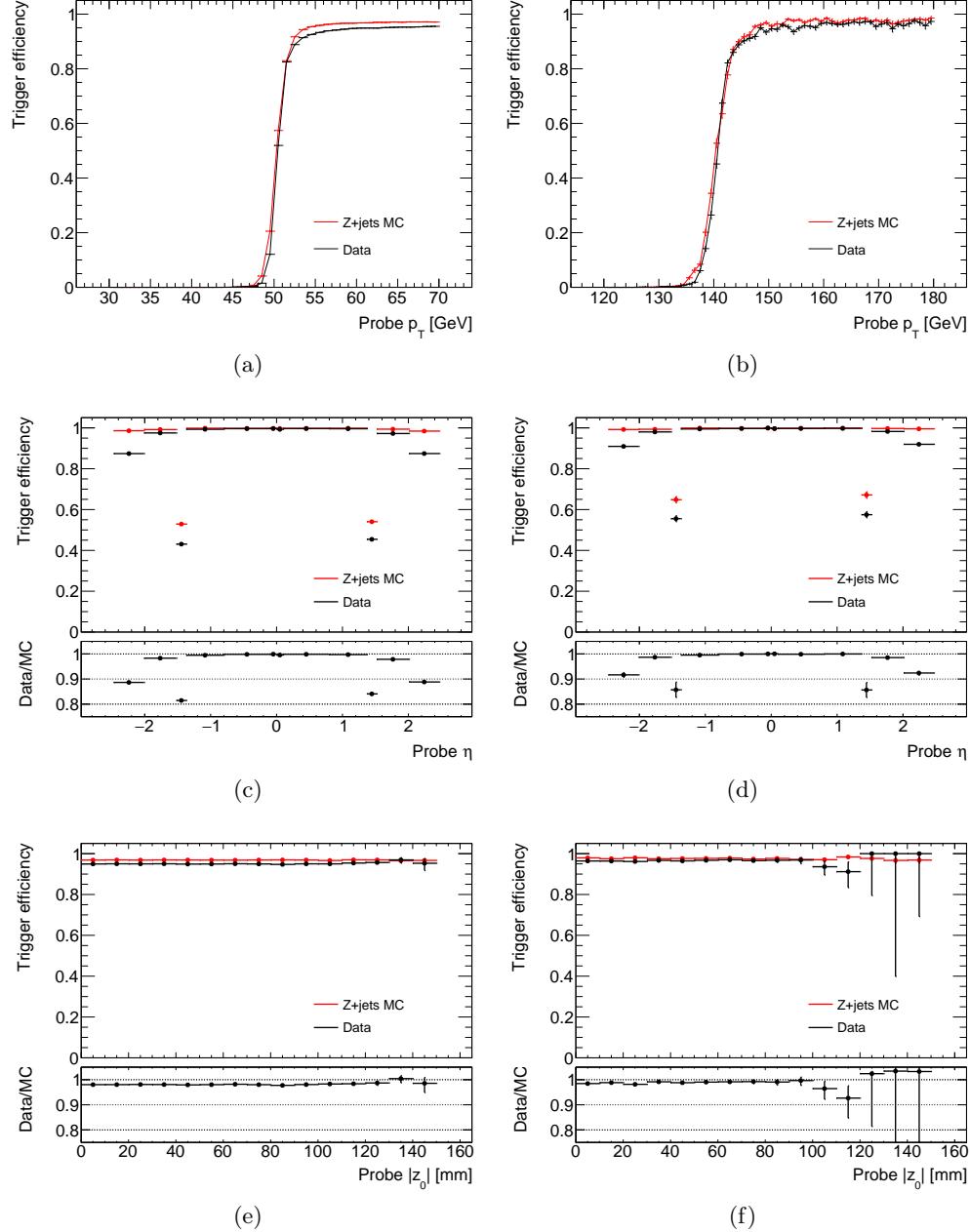


Figure 9.7: Efficiencies of the HLT_g50_loose as a function of probe (a) p_T , (c) η , and (e) $|z_0|$ estimated using the data and $Z+jets$ MC samples. The corresponding plots of the HLT_g140_loose trigger are shown in (b), (d), and (f). Only the pairs with a probe electron in the plateau region of (a) and (b) are considered in the rest.

9.2.2 Muon trigger

The systematic uncertainty of the single muon trigger is estimated with a standard tag-and-probe method on $Z \rightarrow \mu\mu$ events both in data and MC. The selection criteria of muon tag-and-probe candidates are listed in Table 9.3. Similar to the photon triggers, pairs are required to have opposite signs and to satisfy the mass requirement ($|m_{e^+e^-} - m_Z| < 10$ GeV) and the isolation requirement of $\Delta R(\text{tag}, \text{probe}) > 0.4$.

Cut	Tag muon	Probe muon
p_T [GeV] >	28	30
Trigger matched	HLT_mu26_ivarmedium	—
$ \eta <$	2.4	1.05
Identification	Medium	Loose and combined
Isolation	Loose	—
d_0 significance	< 3	—
$\Delta z_0 \sin \theta$	< 0.5mm	—

Table 9.3: Selection criteria for tag-and-probe muons.

The invariant mass distributions of the muon tag-and-probe pairs found in the data and MC samples are shown in Figure 9.8. The shape of distribution is in good agreement with negligible background. Therefore, no background subtraction is performed in the calculation of the trigger efficiency.

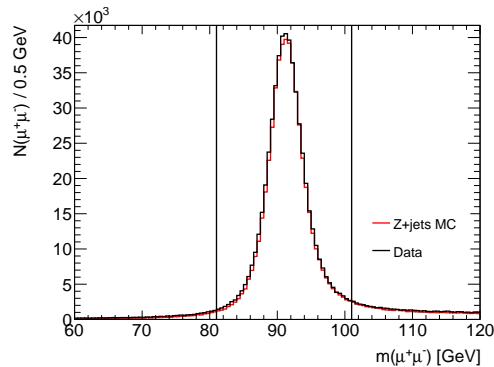


Figure 9.8: Invariant mass distributions of the tag-and-probe muon pairs used to study the efficiencies of the single muon trigger in the data and $Z + \text{jets}$ MC samples. Only the pairs with a probe muon in the plateau region of Figure 9.9a are considered.

The selected tag-and-probe muons are used to estimate the efficiency of the single muon trigger, shown as a function of probe p_T and $|z_0|$ in Figure 9.9. The efficiency in p_T show that the muon trigger plateau starts at 62 GeV. The efficiency in $|z_0|$ shows no dependence of the muon trigger efficiency on $|z_0|$. However, the trigger efficiency in data can be studied up to $|z_0| \approx 150$ mm at which a significant decrease in the efficiency is shown.

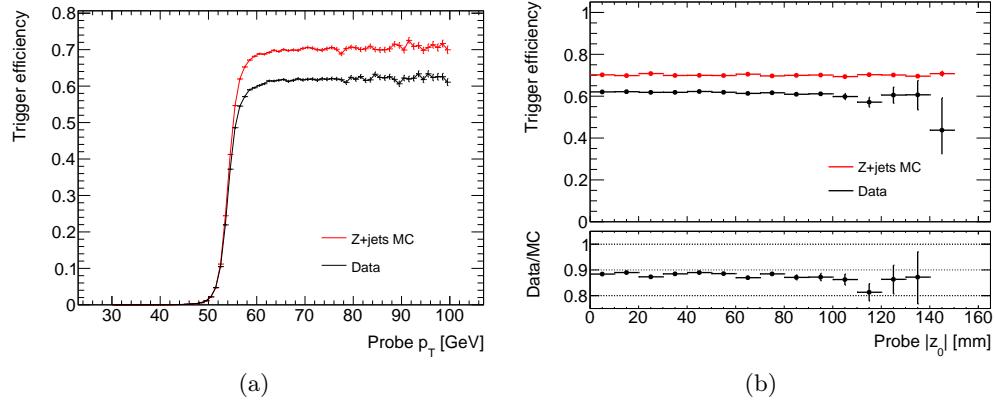


Figure 9.9: Efficiency of the single muon trigger as a function of probe (a) p_T and (b) $|z_0|$ estimated using the data and $Z+jets$ MC samples. Only the pairs with a probe electron in the plateau region of (a) are considered in (b).

Source	Syst. Uncert.
Trigger	-
Track reconstruction	14%
Vertex reconstruction	1%
Total	15%

Table 9.4: Summary table of all systematic uncertainties in the signal efficiency

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A Truth-level p_T and η distributions of Signal MC samples

This appendix contains ...

B K_S yields in data and MC samples used for tracking and vertexing systematic uncertainties

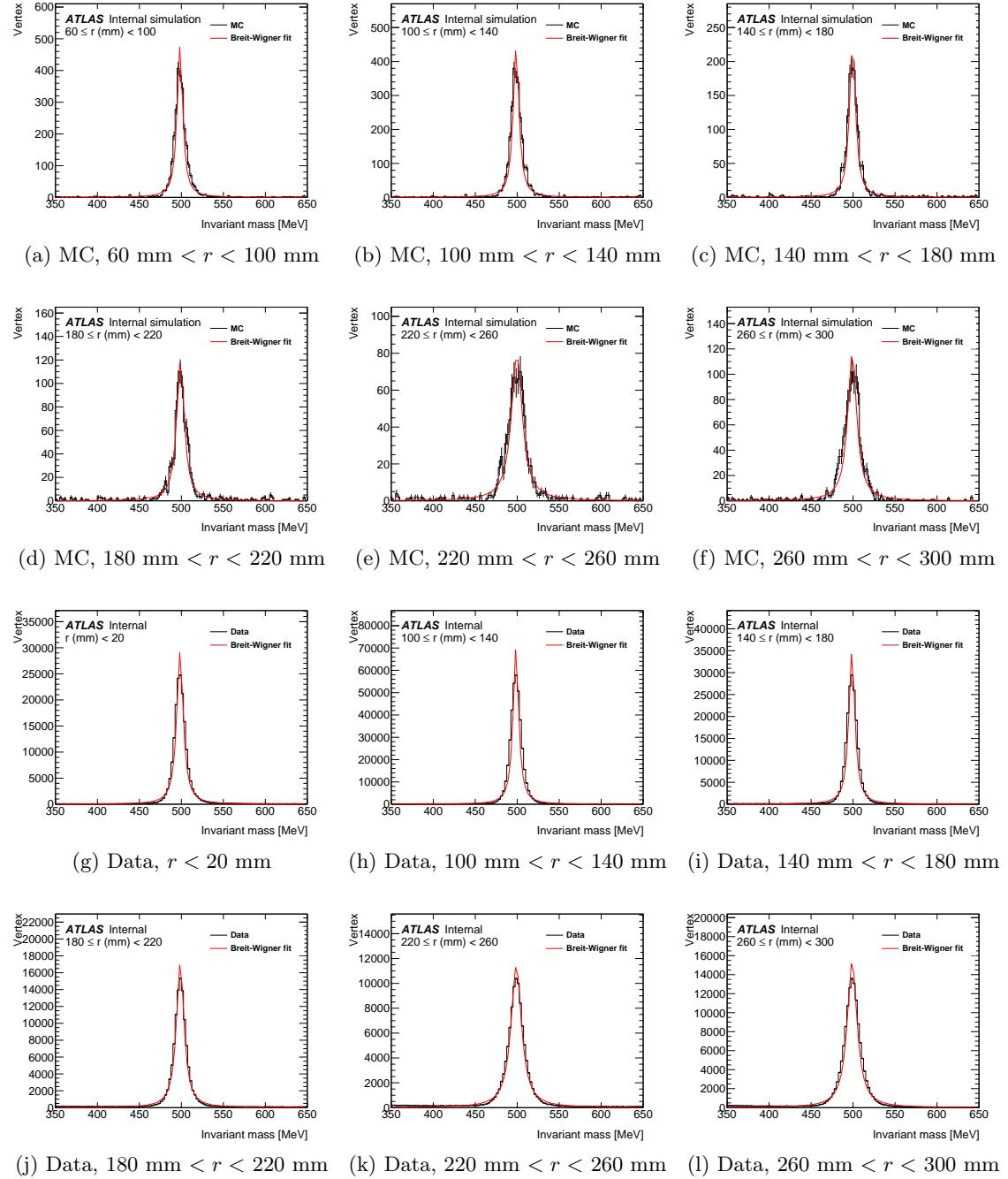


Figure 10: K_S invariant mass for various r . The curve shows a fit to Breit-Wigner.

C K_S and Z' comparison

The ideal K_S sample to estimate the systematic uncertainty in track and vertex reconstruction should have the same kinematic distributions as the Z' MC sample. Obviously, the two samples have different distributions. Figure 11 shows comparisons of the vertex/kinematic distributions. The reconstructed K_S and Z' vertices are required to match to a K_S and Z' vertex produced at truth level with spatial displacement no larger than 0.7 mm. All distributions are normalized to unity. It is fortuitous that their distribution cover the r region of interest, and the two samples have similar z distribution.

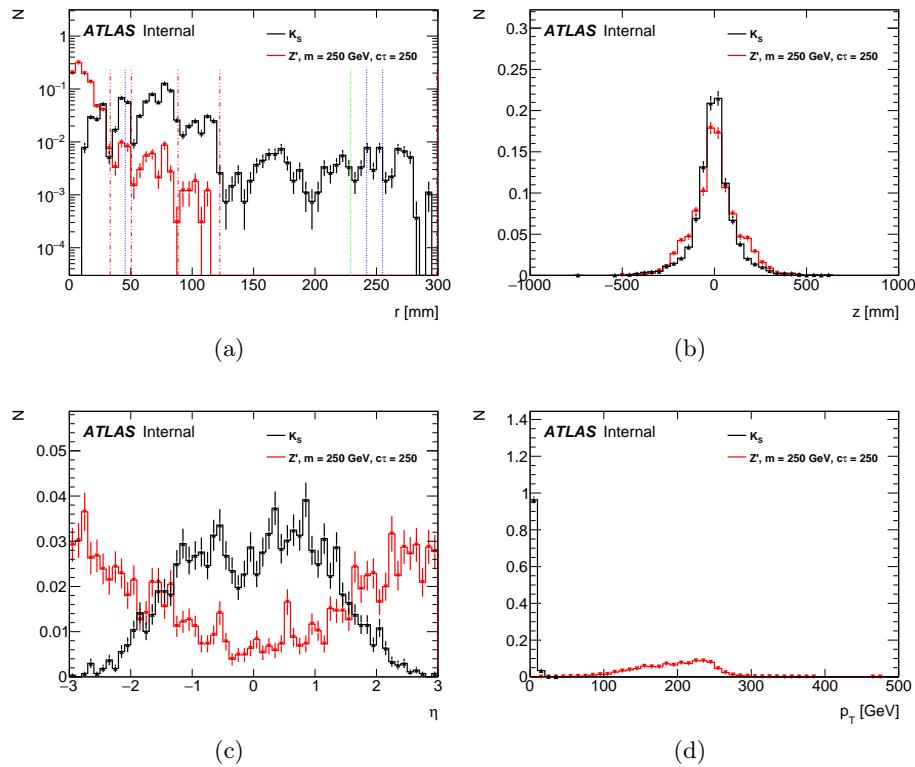


Figure 11: Distribution of transverse (a), longitudinal vertex position (b), η (c), p_T (d), and the opening angle between decay particles of K_S and Z' vertices (e) found in the background and the signal MC sample described in Section ???. Distributions are normalized to unity. Systematic uncertainties are shown.

C.1 Extrapolation from control region

$$\begin{aligned}
N_{\mu x}^{est} &\approx 2 \cdot P(\mu) \cdot N_{xx}^{obs}, \\
N_{ex}^{est} &\approx 2 \cdot P(e) \cdot N_{xx}^{obs}, \\
N_{\mu\mu}^{est} &\approx P(\mu)^2 \cdot N_{xx}^{obs}, \\
N_{ee}^{est} &\approx P(e)^2 \cdot N_{xx}^{obs}, \\
N_{e\mu}^{est} &\approx 2 \cdot P(e) \cdot P(\mu) \cdot N_{xx}^{obs}.
\end{aligned} \tag{3}$$

where N^{obs} and N^{est} represent track-flipping vertex yield and estimated vertex yield by the extrapolation, respectively.

C.2 Extrapolation from validation region

$$\begin{aligned}
N_{\mu\mu}^{est} &\approx \frac{1}{2} \cdot P(\mu) \cdot N_{\mu x}^{obs}, \\
N_{ee}^{est} &\approx \frac{1}{2} \cdot P(e) \cdot N_{ex}^{obs}, \\
N_{e\mu}^{est} &\approx \frac{1}{2} \cdot (P(e) \cdot N_{\mu x}^{obs} + P(\mu) \cdot N_{ex}^{obs})
\end{aligned} \tag{4}$$

C.3 Scale factors

$$\begin{aligned}
S_{xx \rightarrow \mu\mu} &= S_{xx \rightarrow \mu x}^2 \\
S_{xx \rightarrow ee} &= S_{xx \rightarrow ex}^2 \\
S_{xx \rightarrow e\mu} &= \left(\frac{1}{2} (S_{xx \rightarrow \mu x} + S_{xx \rightarrow ex}) \right)^2 \\
S_{\mu x \rightarrow \mu\mu} &= S_{xx \rightarrow \mu x} \\
S_{ex \rightarrow ee} &= S_{xx \rightarrow ex} \\
S_{ex, \mu x \rightarrow e\mu} &= \frac{1}{2} (S_{xx \rightarrow \mu x} + S_{xx \rightarrow ex})
\end{aligned} \tag{5}$$