中国科学技术大学

博士学位论文

在 ATLAS 实验上基于双轻子和不可见末态探测暗物质并精确测量 ZZ 玻色子对产生截面

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完成时间: 二〇二五年十二月十五日

University of Science and Technology of China

A dissertation for doctor's degree

Measurement of ZZ Production Cross-section and Searching for Dark Matter in ATLAS with $\ell^+\ell^- + E_T^{miss}$ Final State

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Finished time: December 15, 2025

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摘　要

在 Higgs 玻色子发现之后, 标准模型的理论趋于完善, 验证标准模型、以及寻找超越标准模型之外的新物理是现在粒子物理的主要课题. W 及 Z 玻色子是负责传递弱核力的基本粒子, 在其 1983 年被发现后一直是标准模型重要的核心组件, 而在大型核子对撞机上, ZZ 玻色子对的产生是非常重要而且占比很大的一个末态, 对其进行观测的主要衰变道为四轻子衰变以及双轻子加不可见末态. 其中双轻子加不可见末态有以下几个特点: 拥有比四轻子高得多的截面, 有助于提高测量过程中的统计量, 提高测量精度; 末态简单, 只包含两个轻子; 物理过程简单, 分析过程. 因此双轻子加不可见末态也成为了对 ZZ 产生截面进行观测的良好末态.

在标准模型下 Higgs 玻色子会有 0.001 的比例衰变到两个 Z 玻色子再到四个中微子, 而在对暗物质的探测中, 在一些超越标准模型之外的理论预言了 Higgs 的不可见衰变, 对于 ZH(inv) 的末态则只会观测到一个可见的 Z 玻色子. 在这个衰变道下的可见末态同样是双轻子加不可见部分, 我们可以通过测量对该末态的比例来观测 Higgs 玻色子进行超越标准模型预言的衰变道的测量, 并给出其上限. 该部分会包含了 spin-1 和 2HDM+a 两个模型的预测, 并给出更为精确的观测上限.

在该文章中, 将使用 ATLAS 在 2015-2018 年收集的 13TeV 积分亮度为 $140 fb^{-1}$ 的对撞数据, 通过对双轻子加不可见末态的分析与测量, 进而得到对 ZZ 产生微分截面的测量. 该测量的结果, 其测量的总产生截面相比于使用 ATLAS 第二次运行早期的测量结果, 其拥有更高的精度, 同时与之前的测量结果相吻合. 同时也使用该收集的数据, 来探测该末态下存在 Higgs 进行超越标准模型衰变的可能性, 并得到现有超越标准模型理论预言的结果并不能显著观测到, 并重新设定 Higgs 玻色子不可见衰变的比例上限.

同时大型强子对撞机正在升级为高亮度大型强子对撞机, 更高的亮度会为新物理的发现带来更多机遇, 同时也对探测器的抗辐照特性, 计数率等方面带来更有挑战性的要求, 因而硬件方面的升级不可或缺. 该文章也收录了作者在 ATLAS 探测器升级过程中, 在小型监测漂移管探测器组装以及测试方面的工作, 这些新的探测器将用于 ATLAS 探测器的升级, 并为大型强子对撞机的下一步运行奠定良好的基础.

关键词: ATLAS　Z 玻色子　暗物质　监测漂移管探测器

ABSTRACT

This thesis undertakes studies based on data collected by the ATLAS experiment at the Large Hadron Collider, corresponding to an integrated luminosity of 140 fb^{-1} at a proton-proton collision energy of $\sqrt{s} = 13$ TeV. The analyses focus on the $\ell^+\ell^- E_T^{miss}$ final state, where $\ell^+\ell^-$ represents either an electron pair (e^+e^-) or a muon pair ($\mu^+\mu^-$) decay from the Z boson, and E_T^{miss} denotes the missing transverse energy. This final state originates from the decay channel of the vector boson pair ZZ, a Standard Model (SM) production process described by $ZZ \to \ell^+\ell^-\nu\bar{\nu}$. This final state may also arise from the hypothetical signal of dark matter particles decaying from the Higgs boson in the production process of $pp \to ZH \to \ell^+\ell^-\chi\bar{\chi}$. In both cases, the neutrino ν and potentially the dark matter particle χ remain undetected, resulting in the experimental signature of missing transverse energy E_T^{miss}.

Two significant physics analyses and results are presented in this thesis in detail. The first focuses on precisely measuring the Standard Model (SM) ZZ production cross-section. This measurement scrutinizes the SM electroweak theory at the highest energy frontier. Additionally, it aims to probe the potential breakdown of the SM by investigating higher-order quantum loop corrections. Particularly, the analysis delves into measuring the anomalous neutral vector boson self-interactions, which could provide insights into deviations from the SM predictions. The second analysis is dedicated to the search for dark matter particles via the ZH production process. Here, the objective is to establish constraints on the invisible Higgs decay branching fraction, offering crucial insights into the possible existence of dark matter.

In the quest to search for dark matter particles through the $pp \to ZH \to \ell^+\ell^-\chi\bar{\chi}$ process, events stemming from the SM $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ process represent the irreducible background. Furthermore, both analyses contend with additional significant backgrounds originating from SM processes such as WW, WZ, $t\bar{t}$, tW, and ttV productions, as well as the Z+jets process. These backgrounds are estimated using data-driven techniques. To enhance sensitivity and diminish background interference in both analyses, multi-variate-analysis methods are employed. These methods serve to refine signal-to-background discrimination. Ultimately, the extraction of final physics results hinges on fitting the observed data with the underlying physics models. This fitting process enables the extraction of meaningful insights into the presence or absence of dark matter particles and other phenomena under investigation.

In addition to the detailed physics analyses presented, this thesis also highlights a significant hardware project related to the ATLAS muon detector upgrade, a critical task in preparation for the high-luminosity phase of the Large Hadron Collider (HL-LHC) expected in 2029. The focus of this work lies in the production and testing of the small-diameter Monitored Drift Tube (sMDT) chambers. The author's contributions span various facets of this undertaking, including the development and implementation of infrastructure for detector construction, the meticulous assembly of precision tubes and chambers, and the rigorous execution of quality control tests. These efforts are integral to ensuring the ATLAS experiment's readiness to capitalize on the enhanced physics potential afforded by the HL-LHC era.

Key Words: LHC, ATLAS, ZZ, Dark Matter, sMDT

Contents

Notation

SM The Standard Model

BSM Beyond the Standard Model

LHC The Large Hadron Collider

$HL-LHC$ High-Luminosity LHC

$ATLAS$ The ATLAS Experiment

Z Z boson

l Lepton

ν Neutrino

Chapter 1 Introduction

1.1 Particle Physics

Particle physics is a subject that focuses on the fundamental properties of elementary particles.

Back in the 1930s, the weak interaction was first postulated in the 1930s to explain beta decay, but the mediate particle remains hidden. After the discovery of CP violation in the WU experiment and the formulation of Yang-Mills theory in 1950s, during 1964-1971, Sheldon Glashow, Abdus Salam, and Steven Weinberg formulated the electroweak theory, which predicted the Z boson as the mediator of neutral current weak interactions. However, the mass of this unknown heavy mediator particle has remained unknown for more than 10 years. In 1983, the Super Proton Synchrotron(SPS) discovered the Z boson in both UA1 and UA2 experiments. This is the first significant verification of the Standard Model(SM), and it keeps an important component of SM.

The Z boson remains the important rule in the Standard Model(SM), and the properties of Z boson are important parameters in the electroweak theory. Measurement of the mass, width, and other properties of the Z boson can provide insights into the electroweak symmetry breaking mechanism.

The precise measurements of the Z boson's decay widths also allow for stringent tests of the SM and constraints on new physics beyond the SM(BSM), which is one of the most compelling challenges in modern particle physics. Since the Standard Model does not account for the presence of DM, which constitutes approximately 27% of the universe's mass-energy content, it hint the theories beyond the Standard Model. Beyond Standard Model (BSM) theories propose various candidates and mechanisms to explain the existence of the dark matter.

Several BSM theories propose particles that could serve as DM candidates. These theories often extend the SM by introducing new particles and interactions. However, the dark matter particles are expected to be neutral and weakly interacting, meaning they won't leave direct signals in the detectors. Therefore, the detection of dark matter relies on observing its decay products or the invisible component resulting from visible parent processes. Current dark matter detection methods at the Large Hadron Collider (LHC) are based on precise measurements of Missing Transverse Energy (MET) and constraints from existing process decay ratios.

Both methods require the high-precision measurement of the existing processes in the SM, as many processes from the expected SM behavior could indicate the presence of dark matter. This precision is crucial for accurately identifying the subtle signals of dark matter among the complex background of SM processes.

1.2 Analyses

1.2.1 Measurement of ZZ Production

The differential cross-section measurement of the process $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ is a crucial component in the study of electroweak interactions and the Higgs mechanism. This process can provide a stringent test of the SM predictions, including the leptonic decay properties of Z boson. Since there are only leptons in the final state, this channel has a clear and distinctive signature that can be precisely measured on the ATLAS detector.

1.2.2 Search for Dark Matter with $ll + E_T^{miss}$ Final State

The $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel plays an important rule in the search for DM with the following several reasons:

1. **Clean Signature**: The final state with two charged leptons and missing energy provides a clean and relatively background-free signature. The charged leptons can be precisely measured, and the missing energy can be attributed to neutrinos and potential DM particles.
2. **Sensitivity to New Physics**: The presence of missing energy makes this channel highly sensitive to new physics scenarios, including those predicting DM production. Deviations from the SM predictions in the measured differential cross-sections can signal the existence of BSM particles.
3. **Complementary to Other Searches**: While direct detection experiments aim to observe DM interactions with ordinary matter, collider searches like those involving the $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ channel provide complementary information by attempting to produce DM particles directly. This multi-faceted approach increases the likelihood of discovering DM.

The study of the $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ decay channel is vital for probing BSM theories and searching for DM. By leveraging the clean signature and sensitivity to missing energy, physicists can test various DM candidates and models. This channel, combined with other experimental searches, enhances the potential to uncover the nature of dark matter and extend our understanding beyond the Standard Model.

1.3 Hardware Work

Chapter 2 The Standard Model of Particle Physics

2.1 Standard Model

The Standard Model (SM) of particle physics is the theoretical framework that describes the fundamental particles and their interactions, excluding gravity. It is one of the most successful theories in physics, providing precise predictions that have been confirmed by numerous experiments.

2.1.1 Fundamental Particles

The SM classifies all known elementary particles into two broad categories: fermions and bosons.

1. **Fermions**: These are the building blocks of matter. They follow the Pauli exclusion principle and are categorized into quarks and leptons. Quarks: There are six types (flavors) of quarks: up (u), down (d), charm (c), strange (s), top (t), and bottom (b). Quarks combine to form hadrons, such as protons and neutrons.
2. **Bosons**: These are force carriers that mediate interactions between fermions. Gauge Bosons: The SM includes four gauge bosons corresponding to the three fundamental forces (excluding gravity): Photon (γ): Mediates the electromagnetic force. W and Z bosons ($W^{\pm}Z^{0}$): Mediate the weak nuclear force. Gluon (g): Mediates the strong nuclear force. Higgs Boson: Discovered in 2012, the Higgs boson (H) is associated with the Higgs field, which gives mass to other particles through the Higgs mechanism.

2.1.2 Fundamental Forces

The SM describes three of the four fundamental forces in nature:

1. **Electromagnetic Force**: Described by Quantum Electrodynamics (QED), it acts between charged particles and is mediated by photons.
2. **Weak Nuclear Force**: Responsible for processes like beta decay, it is mediated by the W and Z bosons. The weak force can change the flavor of quarks, thus playing a crucial role in nuclear reactions.
3. **Strong Nuclear Force**: Described by Quantum Chromodynamics (QCD), it binds quarks together to form hadrons. Gluons mediate this force and carry color charge.

2.1.3 Math Theory Framework

The SM is a quantum field theory (QFT), specifically a gauge theory, based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$

1. $SU(3)_C$: The symmetry group of QCD, describing the strong interactions between quarks and gluons.
2. $SU(2)_L \times U(1)_Y$: The electroweak symmetry, describing the unified description of the electromagnetic and weak interactions. This symmetry is spontaneously broken by the Higgs mechanism, giving masses to the W and Z bosons while leaving the photon massless.

Besides the gauge theory, the Higgs mechanism is central to the SM. It explains how particles acquire mass, and it's deatiled introduced in 2.2.1.

2.1.4 Di-boson Production

2.2 Beyond the Standard Model and Dark Matter Search

While the SM is remarkably successful, it is not complete. It does not include gravity, described by General Relativity, nor does it explain dark matter, dark energy, or the matter-antimatter asymmetry in the universe. These limitations suggest the need for a more comprehensive theory, such as string theory or other beyond the Standard Model (BSM) theories like supersymmetry (SUSY).

2.2.1 BSM Theory

1. **Supersymmetry (SUSY)**: SUSY extends the SM by postulating a symmetry between fermions and bosons. The lightest supersymmetric particle (LSP), often the neutralino, is a stable, electrically neutral particle and a prime candidate for DM. The production of neutralinos in collider experiments could manifest as missing transverse energy (E_T^{miss}) in events, making processes like $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ crucial for detecting such signals.
2. **Extra Dimensions**: Theories involving extra spatial dimensions, such as the Large Extra Dimensions (LED) model, predict the existence of Kaluza-Klein (KK) excitations. These KK particles could contribute to the DM relic density and might be produced in ZZ decays, leading to signatures with large E_T^{miss}.
3. **Hidden Sector Models**: Hidden sector or dark sector models introduce new particles that interact weakly with SM particles through a mediator, such as a dark photon. The production of these mediators in ZZ decays could result in final

states with leptons and missing energy, indicative of DM particles escaping detection.

2.3 Higgs-related mechanism/theory

The Higgs mechanism is a process by which gauge bosons in certain gauge theories acquire mass through spontaneous symmetry breaking. It is a central part of the Standard Model of particle physics, explaining how particles like the W and Z bosons gain mass while the photon remains massless.

The Higgs Field and Potential

The Higgs field is a complex scalar field, often denoted by ϕ, which is an $SU(2)$ doublet with four real degrees of freedom. The Higgs field can be written as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

The potential for the Higgs field is given by:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

where μ^2 and λ are constants. For the Higgs mechanism to work, μ^2 must be negative ($\mu^2 < 0$) and $\lambda > 0$.

Spontaneous Symmetry Breaking

The Higgs potential has a non-zero vacuum expectation value (VEV). The potential $V(\phi)$ has a "Mexican hat" shape, and the minimum is not at $\phi = 0$, but at some non-zero value:

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

where v is the VEV given by:

$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

Gauge Boson Masses

The covariant derivative of the Higgs field in the electroweak theory is:

$$D_\mu \phi = \left(\partial_\mu - \frac{i}{2} g W_\mu^a \tau^a - \frac{i}{2} g' B_\mu \right) \phi$$

where W_μ^a (with $a = 1, 2, 3$) are the $SU(2)_L$ gauge fields, B_μ is the $U(1)_Y$ gauge field, g is the $SU(2)_L$ coupling constant, g' is the $U(1)_Y$ coupling constant, and τ^a are the Pauli matrices.

When the Higgs field acquires a VEV, the gauge boson mass terms are generated from the kinetic term of the Higgs field:

$$(D_\mu \phi)^\dagger (D_\mu \phi)$$

Expanding this term and substituting the VEV, we obtain the mass terms for the gauge bosons:

$$\frac{1}{2} g^2 v^2 \left(W_\mu^1 W^{\mu 1} + W_\mu^2 W^{\mu 2} \right) + \frac{1}{2} \left(\frac{1}{2} g W_\mu^3 - \frac{1}{2} g' B_\mu \right)^2 v^2$$

This results in the masses of the W and Z bosons:

$$M_W = \frac{1}{2} g v$$

$$M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$

while the photon remains massless:

$$M_\gamma = 0$$

Higgs Boson

The Higgs field also manifests as a physical particle, the Higgs boson H. After symmetry breaking, the Higgs field can be written as:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

The Higgs boson mass is given by:

$$M_H = \sqrt{2\lambda} v$$

Summary

The Higgs mechanism provides a way for gauge bosons to acquire mass through spontaneous symmetry breaking of the Higgs field. This process preserves the gauge invariance of the theory while giving mass to the W and Z bosons, with the photon remaining massless. The discovery of the Higgs boson at the LHC in 2012 was a crucial confirmation of this mechanism and a significant milestone in particle physics. And the mass of Higgs boson remains the important position in the SM theory since the discovery in 2012.

Chapter 3　The LHC and ATLAS Experiment

3.1　The Large Hadron Collider

3.1.1　High-Luminosity LHC Upgrade

3.1.2　Collider Physics

3.2　The ATLAS Detector

3.2.1　Inner Tracker

3.2.2　Calorimetry

3.2.3　Muon Spectrometer

3.2.4　Magnet System

3.2.5

Chapter 4 Measurement of ZZ Production with $ll\nu\nu$ Final State

4.1 Monte Carlo and Data Samples

This chapter details the datasets and simulated samples employed in the analysis. The measurement is performed on the full proton-proton (pp) collision dataset recorded by the ATLAS experiment during Run 2 of the Large Hadron Collider (LHC) at a centre-of-mass energy of $\sqrt{s} = 13$ TeV.

Monte Carlo (MC) simulations are essential for modeling the kinematic and topological properties of the signal process and for estimating the contributions from all significant Standard Model backgrounds. A cornerstone of the analysis methodology is the consistent application of object reconstruction, calibration, and event selection criteria to both the data and the simulated samples. This unified treatment ensures that a direct and unbiased comparison can be made between the observed data and the theoretical predictions, allowing for the extraction of the physics results.

The following sections will first provide a comprehensive overview of the MC samples generated for the signal and various background processes. Subsequently, the data samples, data quality requirements, and the trigger strategy employed to select events for this analysis will be detailed.

4.1.1 Monte Carlo Samples

The estimation of signal efficiencies and background contributions relies on a diverse set of Monte Carlo (MC) event samples. These samples are generated to correspond to the 2015–2018 data-taking periods and are processed through the same reconstruction software and calibration procedures as the collision data. This ensures a consistent treatment of physics objects and allows for a direct comparison between observation and prediction. The following sections describe the general simulation framework before detailing the specific samples used to model signal and background processes.

1. The ATLAS Simulation Framework

The production of simulated events in ATLAS follows a well-established multi-step procedure, ensuring a high-fidelity representation of proton-proton collisions and the subsequent detector response. This simulation chain consists of three main stages:

1. **Event Generation:** The initial hard-scatter interaction is simulated using a variety of event generators. These generators compute the matrix element (ME) for a specific physics process, often to Next-to-Leading Order (NLO) or Leading Order (LO) in perturbative QCD. The ME calculation is then interfaced with a parton shower (PS) algorithm, such as those provided by `PYTHIA 8`[1] or the one internal to `Sherpa`[2], which models initial- and final-state radiation, multiple parton

interactions, hadronisation, and particle decays. The specific generator, perturbative order, and Parton Distribution Function (PDF) set used for each sample are chosen to provide the most accurate description of the process.

2. **Detector Simulation:** The stable particles generated in the first step are propagated through a detailed model of the ATLAS detector geometry and material composition using the `Geant4` toolkit[3]. This stage simulates the interactions of particles with the active and passive elements of the detector, resulting in simulated energy deposits and "hits" in the various sub-systems.
3. **Digitisation and Reconstruction:** The simulated hits are converted into digitised electronic signals that emulate the real detector readout. To account for the high-luminosity environment of the LHC, multiple inelastic *pp* collisions, known as pile-up, are overlaid on each hard-scatter event. These pile-up events are simulated with `PYTHIA 8` using the A3 tune[4] and the `NNPDF2.3LO` PDF set[5]. The distribution of the number of pile-up interactions is weighted to match that observed in the data. Finally, the same reconstruction algorithms used for collision data are applied to the digitised output to reconstruct high-level physics objects such as electrons, muons, jets, and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$).

Correction factors, or scale factors, are applied to all simulated samples to account for small differences in trigger, reconstruction, and identification efficiencies between data and MC simulation.

2. Signal Samples

The analysis targets the measurement of the SM ZZ production cross-section in the $\ell^+\ell^-\nu\bar{\nu}$ final state and searches for BSM physics through anomalous gauge boson couplings.

(1) Standard Model *ZZ* Production

The primary signal process is the production of a pair of Z bosons decaying to $\ell^+\ell^-\nu\bar{\nu}$. This includes both quark-antiquark initiated and loop-induced gluon-gluon fusion processes, which are simulated with `Sherpa 2.2.2`. Electroweak ZZ production in association with two jets is modelled separately with `MadGraph5`. Details of these samples are provided in Table 4.1.

(2) Anomalous Gauge Couplings

The search for new physics is performed by probing for anomalous neutral triple gauge couplings (nTGC) and anomalous quartic gauge couplings (aQGC) using an Effective Field Theory (EFT) framework. A dedicated set of MC samples has been generated to model the kinematic effects of these BSM operators. The samples used for the nTGC and aQGC searches are listed in Tables 4.2 and 4.3, respectively.

Table 4.1 Summary of Monte Carlo samples used to model the SM $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ signal components. Cross-sections (σ) are provided by the generator, and k-factors are applied to correct to higher-order predictions.

Process	DSID	Generator	σ [pb]	k-factor
$gg \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$	345723	Sherpa 2.2.2	0.0071108	1.7
$q\bar{q} \to ZZ/\gamma^* \to \ell^+\ell^-\nu\bar{\nu}$	345666	Sherpa 2.2.2	0.49908	1.5
Electroweak $ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$	363724	MadGraph5	0.0013529	-

Table 4.2 List of samples generated for the study of anomalous Neutral Triple Gauge Couplings (nTGCs).

Process	DSID
nunull_f4gamma_plus0001	367911
nunull_f4Z_plus0001	367912
nunull_f5gamma_plus0001	367913
nunull_f5Z_plus0001	367914
nunull_sm	367915

Table 4.3 List of samples generated for the study of anomalous Quartic Gauge Couplings (aQGCs).

Process	DSID
aQGCFT0_INT_05_ZZ_llvv	515527
aQGCFT0_QUAD_05_ZZ_llvv	515528
aQGCFT1_INT_1_ZZ_llvv	515529
aQGCFT1_QUAD_1_ZZ_llvv	515530
aQGCFT2_INT_1_ZZ_llvv	515531
aQGCFT2_QUAD_1_ZZ_llvv	515532
aQGCFT5_INT_1_ZZ_llvv	515533
aQGCFT5_QUAD_1_ZZ_llvv	515534
aQGCFT6_INT_1_ZZ_llvv	515535
aQGCFT6_QUAD_1_ZZ_llvv	515536
aQGCFT7_INT_1_ZZ_llvv	515537
aQGCFT7_QUAD_1_ZZ_llvv	515538
aQGCFT8_INT_1_ZZ_llvv	515539
aQGCFT8_QUAD_1_ZZ_llvv	515540
aQGCFT9_INT_2_ZZ_llvv	515541
aQGCFT9_QUAD_2_ZZ_llvv	515542

3. Background Samples

Backgrounds to the $\ell^+\ell^- + E_{\mathrm{T}}^{\mathrm{miss}}$ final state are broadly categorised as either featuring prompt leptons and genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ (irreducible) or arising from misidentified objects or detector mismeasurement (reducible). The MC samples used to model these processes are detailed in the following tables.

（1） Diboson and Triboson Backgrounds

The production of WZ, WW, and $ZZ \to \ell^+\ell^-\ell^+\ell^-$ represent the most significant irreducible backgrounds. Smaller contributions from triboson processes (WWW,

WWZ, WZZ, ZZZ) are also considered. These processes are primarily simulated with `Sherpa` and `Powheg+Pythia8`. Summaries are provided in Tables 4.4, 4.5, and 4.6.

(2) Top Quark Backgrounds

Events from top-antitop ($t\bar{t}$) and single-top production are a significant source of background, primarily from their dileptonic decay channels. Associated production with a vector boson ($t\bar{t}V$) also contributes. These are simulated with `Powheg+Pythia8` and `MadGraph5_aMC@NLO`, as detailed in Tables 4.7 and 4.8.

(3) Z/γ^*+jets Background

This is the dominant reducible background, arising from Drell-Yan events with large, mismeasured $E_{\mathrm{T}}^{\mathrm{miss}}$. It is modelled using `Sherpa 2.2.1` with NLO-accurate matrix elements. Samples are generated in slices of the partonic transverse momentum sum and separated by lepton flavour, as shown in Tables 4.9, 4.10, and 4.11.

(4) Higgs Boson Backgrounds

Processes involving the production of a Higgs boson can also contribute to the selected final state. These minor backgrounds are simulated with `Powheg+Pythia8` and are listed in Table 4.12.

Table 4.4 Summary of ZZ background samples, including the four-lepton final state.

Process	DSID	Generator	σ [pb]	k-factor
$gg \to ZZ \to 4\ell$	345706	Sherpa 2.2.2	0.010091	1.7
$q\bar{q} \to ZZ/\gamma^* \to 4\ell$	364250	Sherpa 2.2.2	1.2522	-
$q\bar{q} \to ZZ \to q\bar{q}\ell^+\ell^-$	363356	Sherpa 2.2.1	15.565	0.1419

Table 4.5 Summary of WZ and WW background samples.

Process	DSID	Generator	σ [pb]	k-factor
$WZ \to \ell\nu\ell^+\ell^-$	364253	Sherpa 2.2.2	4.5718	-
$WZjj \to \ell\nu\ell^+\ell^- jj$	364284	Sherpa 2.2.2	0.047385	-
$WZ \to q\bar{q}\ell^+\ell^-$	363358	Sherpa 2.2.1	3.4328	-
$q\bar{q} \to WW \to \ell\nu\ell\nu$	361600	Powheg+Pythia8	10.631	-
$q\bar{q} \to WW \to q\bar{q}\ell\nu$	361606	Powheg+Pythia8	44.18	-
$gg \to WW \to \ell\nu\ell\nu$	345718	Sherpa 2.2.2	0.4823	-

Table 4.6 Summary of triboson (VVV) background samples.

Process	DSID	Generator	σ [pb]	k-factor
$WWW \to 3\ell 3\nu$	364242	Sherpa 2.2.2	0.0071997	-
$WWZ \to 4\ell 2\nu$	364243	Sherpa 2.2.2	0.0017973	-
$WWZ \to 2\ell 4\nu$	364244	Sherpa 2.2.2	0.0035481	-
$WZZ \to 5\ell 1\nu$	364245	Sherpa 2.2.2	0.00018812	-
$WZZ \to 3\ell 3\nu$	364246	Sherpa 2.2.2	0.0016664	0.44594
$ZZZ \to 6\ell$	364247	Sherpa 2.2.2	1.4458e-05	-
$ZZZ \to 4\ell 2\nu$	364248	Sherpa 2.2.2	0.00038556	-
$ZZZ \to 2\ell 4\nu$	364249	Sherpa 2.2.2	0.00038491	0.44479

Table 4.7 Summary of $t\bar{t}$ and single-top background samples.

Process	DSID	Generator	σ [pb]	k-factor
$t\bar{t}$	410472	Powheg+Pythia8	729.77	0.12020
single top (s-channel)	410644	Powheg+Pythia8	2.027	-
single anti-top (s-channel)	410645	Powheg+Pythia8	1.2674	-
single top (t-channel)	410658	Powheg+Pythia8	36.996	-
single anti-top (t-channel)	410659	Powheg+Pythia8	22.175	-
Wt (dilepton)	410648	Powheg+Pythia8	3.997	-
$W\bar{t}$ (dilepton)	410649	Powheg+Pythia8	3.993	-

Table 4.8 Summary of background samples for associated production of top quarks with vector bosons.

Process	DSID	Generator	σ [pb]	k-factor
$t\bar{t}Z, Z \to \nu\nu$	410156	MG5_aMC@NLO+Pythia8	0.15497	-
$t\bar{t}Z, Z \to q\bar{q}$	410157	MG5_aMC@NLO+Pythia8	0.52821	-
$t\bar{t}W$	410155	MG5_aMC@NLO+Pythia8	0.5483	1.1
$t\bar{t}WW$	410081	MadGraph+Pythia8	0.0080975	1.2231

Table 4.9 Summary of the $Z/\gamma^* \to e^+e^-$+jets background samples generated with `Sherpa 2.2.1`.

Process Slice	DSID	σ [pb]	k-factor
$Z \to ee$, $H_{T,parton} < 70$ GeV, CVetoBVeto	364114	1981.8	0.8006
$Z \to ee$, $H_{T,parton} < 70$ GeV, CFilterBVeto	364115	1980.8	0.1101
$Z \to ee$, $H_{T,parton} < 70$ GeV, BFilter	364116	1981.7	0.0622
$Z \to ee$, $70 < H_{T,parton} < 140$ GeV, CVetoBVeto	364117	110.5	0.6732
$Z \to ee$, $70 < H_{T,parton} < 140$ GeV, CFilterBVeto	364118	110.63	0.1792
$Z \to ee$, $70 < H_{T,parton} < 140$ GeV, BFilter	364119	110.31	0.1116
$Z \to ee$, $140 < H_{T,parton} < 280$ GeV, CVetoBVeto	364120	40.731	0.5992
$Z \to ee$, $140 < H_{T,parton} < 280$ GeV, CFilterBVeto	364121	40.67	0.2247
$Z \to ee$, $140 < H_{T,parton} < 280$ GeV, BFilter	364122	40.643	0.1459
$Z \to ee$, $280 < H_{T,parton} < 500$ GeV, CVetoBVeto	364123	8.6743	0.5474
$Z \to ee$, $280 < H_{T,parton} < 500$ GeV, CFilterBVeto	364124	8.6711	0.2564
$Z \to ee$, $280 < H_{T,parton} < 500$ GeV, BFilter	364125	8.6766	0.1679
$Z \to ee$, $500 < H_{T,parton} < 1000$ GeV	364126	1.8081	0.9751
$Z \to ee$, $H_{T,parton} > 1000$ GeV	364127	0.14857	0.9751

Table 4.10 Summary of the $Z/\gamma^* \to \mu^+\mu^-$+jets background samples generated with `Sherpa 2.2.1`.

Process Slice	DSID	σ [pb]	k-factor
$Z \to \mu\mu$, $H_{T,parton}$ < 70 GeV, CVetoBVeto	364100	1983.0	0.8016
$Z \to \mu\mu$, $H_{T,parton}$ < 70 GeV, CFilterBVeto	364101	1978.4	0.1103
$Z \to \mu\mu$, $H_{T,parton}$ < 70 GeV, BFilter	364102	1982.2	0.0626
$Z \to \mu\mu$, 70 < $H_{T,parton}$ < 140 GeV, CVetoBVeto	364103	108.92	0.6716
$Z \to \mu\mu$, 70 < $H_{T,parton}$ < 140 GeV, CFilterBVeto	364104	109.42	0.1813
$Z \to \mu\mu$, 70 < $H_{T,parton}$ < 140 GeV, BFilter	364105	108.91	0.1109
$Z \to \mu\mu$, 140 < $H_{T,parton}$ < 280 GeV, CVetoBVeto	364106	39.878	0.5938
$Z \to \mu\mu$, 140 < $H_{T,parton}$ < 280 GeV, CFilterBVeto	364107	39.795	0.2273
$Z \to \mu\mu$, 140 < $H_{T,parton}$ < 280 GeV, BFilter	364108	39.908	0.1425
$Z \to \mu\mu$, 280 < $H_{T,parton}$ < 500 GeV, CVetoBVeto	364109	8.5375	0.5451
$Z \to \mu\mu$, 280 < $H_{T,parton}$ < 500 GeV, CFilterBVeto	364110	8.5403	0.2587
$Z \to \mu\mu$, 280 < $H_{T,parton}$ < 500 GeV, BFilter	364111	8.4932	0.1712
$Z \to \mu\mu$, 500 < $H_{T,parton}$ < 1000 GeV	364112	1.7881	0.9751
$Z \to \mu\mu$, $H_{T,parton}$ > 1000 GeV	364113	0.14769	0.9751

Table 4.11 Summary of the $Z/\gamma^* \to \tau^+\tau^-$+jets background samples generated with `Sherpa 2.2.1`.

Process Slice	DSID	σ [pb]	k-factor
$Z \to \tau\tau$, $H_{T,parton}$ < 70 GeV, CVetoBVeto	364128	1981.6	0.8010
$Z \to \tau\tau$, $H_{T,parton}$ < 70 GeV, CFilterBVeto	364129	1978.8	0.1103
$Z \to \tau\tau$, $H_{T,parton}$ < 70 GeV, BFilter	364130	1981.8	0.0628
$Z \to \tau\tau$, 70 < $H_{T,parton}$ < 140 GeV, CVetoBVeto	364131	110.37	0.6717
$Z \to \tau\tau$, 70 < $H_{T,parton}$ < 140 GeV, CFilterBVeto	364132	110.51	0.1783
$Z \to \tau\tau$, 70 < $H_{T,parton}$ < 140 GeV, BFilter	364133	110.87	0.1081
$Z \to \tau\tau$, 140 < $H_{T,parton}$ < 280 GeV, CVetoBVeto	364134	40.781	0.5931
$Z \to \tau\tau$, 140 < $H_{T,parton}$ < 280 GeV, CFilterBVeto	364135	40.74	0.2233
$Z \to \tau\tau$, 140 < $H_{T,parton}$ < 280 GeV, BFilter	364136	40.761	0.1311
$Z \to \tau\tau$, 280 < $H_{T,parton}$ < 500 GeV, CVetoBVeto	364137	8.5502	0.5464
$Z \to \tau\tau$, 280 < $H_{T,parton}$ < 500 GeV, CFilterBVeto	364138	8.6707	0.2559
$Z \to \tau\tau$, 280 < $H_{T,parton}$ < 500 GeV, BFilter	364139	8.6804	0.1688
$Z \to \tau\tau$, 500 < $H_{T,parton}$ < 1000 GeV	364140	1.8096	0.9751
$Z \to \tau\tau$, $H_{T,parton}$ > 1000 GeV	364141	0.14834	0.9751

Table 4.12 List of background samples from Higgs boson production processes.

Process	DSID	Generator
$WH, H \to WW, W \to q\bar{q}', H \to \ell\nu\ell\nu$	346560	Powheg+Pythia8
$WH, H \to WW, W \to \ell\nu, H \to \ell\nu q\bar{q}'$	346561	Powheg+Pythia8

4.1.2 Data Samples

The Run II pp collision data collection by the ATLAS experiment starts from 2015, and ends in 2018. This analysis uses the full Run II pp collision data using Release 21 reconstruction, which pass the final Good Run List (GRL) released by the Data Quality group for 2015-2018.

Table 4.13 Good Run Lists (GRLs) used in the analysis.

Data Period	Run Range	GRL File Path
data15_13TeV	276262–284484	GoodRunsLists/data15_13TeV/20170619/PHYS_StandardGRL_All_Good_25ns_276262-284484_OflLumi-13TeV-008.root
data16_13TeV	297730–311481	GoodRunsLists/data16_13TeV/20180129/PHYS_StandardGRL_All_Good_25ns_297730-311481_OflLumi-13TeV-009.root
data17_13TeV	—	GoodRunsLists/data17_13TeV/20180619/physics_25ns_Triggerno17e33prim.lumicalc.OflLumi-13TeV-010.root
data18_13TeV	—	GoodRunsLists/data18_13TeV/20180924/physics_25ns_Triggerno17e33prim.lumicalc.OflLumi-13TeV-001.root

To ensure a high and robust acceptance for events containing one or more energetic leptons, a selection based on a logical disjunction (OR) of multiple trigger paths is applied. The trigger strategy combines both single-lepton and di-lepton-seeded triggers to maximize efficiency across a broad kinematic phase space.

This approach is crucial for retaining signal events where individual lepton transverse momenta may fall below the thresholds of the highest-p_T single-lepton triggers. The specific trigger menus are tailored to each data-taking period to accommodate the evolving LHC running conditions and the corresponding adjustments to the ATLAS trigger system. The comprehensive list of electron and muon triggers utilized in this analysis is enumerated in Table 4.14

Table 4.14 Single-lepton triggers used for this analysis by data period and lepton flavor.

Year	Electron Triggers	Muon Triggers
2015	HLT_e24_lhmedium_L1EM20VH_OR _e60_lhmedium_OR_e120_lhloose	HLT_mu20_iloose_L1MU15_OR _mu50
2016	HLT_e26_lhtight_nod0_ivarloose_OR _e60_lhmedium_nod0_OR _e140_lhloose_nod0 HLT_e24_lhmedium_nod0_L1EM20VH	HLT_mu24_ivarmedium_OR_mu50
2017	HLT_e26_lhtight_nod0_ivarloose_OR _e60_lhmedium_nod0_OR _e140_lhloose_nod0	HLT_mu26_ivarmedium_OR_mu50
2018	HLT_e26_lhtight_nod0_ivarloose_OR _e60_lhmedium_nod0_OR _e140_lhloose_nod0	HLT_mu26_ivarmedium_OR_mu50

4.2 Object and Event Selection

To isolate the rare signal process from the vast number of particles produced in proton-proton collisions, a rigorous procedure is required to identify and select the final-state objects of interest. This procedure begins with the reconstruction of physics objects—including electrons, muons, and jets—from the electronic signals collected by the ATLAS detector. Following reconstruction, a stringent set of selection criteria is applied to ensure the high quality of these objects and to suppress contributions from misidentified particles and background processes, thereby enhancing the purity of the event sample.

This chapter details the complete selection strategy, which is performed in two sequential stages. First, the criteria for selecting individual physics objects are defined, forming a clean and calibrated set of inputs for the analysis. Second, these objects are used to construct an event-level selection designed to isolate the distinct signal topology and define the final signal regions.

The specific implementation of these selections adheres to the official recommendations of the ATLAS collaboration and is performed using AnalysisBase release 21.2.164. The analysis is conducted on STDM3 DAOD (Derived Analysis Object Data) samples, with r-tags r9364/r10201/r10724 corresponding to the MC16a/d/e campaigns.

4.2.1 Object Selection

The successful identification of the signal final state relies on the precise reconstruction and selection of its constituent physics objects from the complex collision environment. This section details the criteria applied to select the muons, electrons, and jets that form the basis of the analysis. A final step resolves any spatial ambiguities between these selected objects to ensure each is uniquely defined. All selections adhere to the recommendations provided by the ATLAS Combined Performance groups.

1. Muons

Muons are reconstructed as *combined muons*, which involves matching a track identified in the inner detector (ID) with a corresponding track in the muon spectrometer. This combined fit provides a high-purity and well-measured muon candidate.

Signal muons selected for this analysis are required to satisfy a stringent set of criteria to ensure they are prompt (originating from the primary interaction) and well-isolated.

- **Kinematics:** Muons must have a transverse momentum $p_T > 20$ GeV and be within the detector acceptance of $|\eta| < 2.5$.

- **Identification:** The ‘Medium‘ identification working point is required. This selection imposes quality requirements on the track fit and the compatibility between the ID and muon spectrometer measurements, effectively suppressing contamination from misidentified hadrons.
- **Purity:** To reject non-prompt muons from heavy-flavour decays and cosmic-ray muons, requirements are placed on the track's impact parameters with respect to the primary vertex: the transverse impact parameter significance $|d_0/\sigma(d_0)| < 3$ and the longitudinal impact parameter $|z_0 \cdot \sin(\theta)| < 0.5$ mm.
- **Isolation:** To ensure the muon is not part of a jet, an isolation requirement is applied. This is based on the sum of track and calorimeter energy deposits in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the muon. The ‘FixedCutPflowLoose‘ working point is used, which corresponds to an efficiency of approximately 99% for high-p_T muons.

To account for differences between data and simulation, dedicated scale and smearing corrections are applied to the muon momentum, and efficiency scale factors are used to correct the Monte Carlo event yields. In addition, a looser ”baseline” selection ($p_T > 7$ GeV, ‘Loose‘ identification) is used to define muons for event vetoes.

2. Electrons

Electrons are reconstructed by matching a track in the inner detector to an energy cluster in the electromagnetic calorimeter. Signal electrons are selected based on the following criteria:

- **Kinematics:** Electrons must have $p_T > 20$ GeV and be reconstructed within the fiducial pseudorapidity range of $|\eta| < 2.47$.
- **Identification:** A likelihood-based discriminant, which combines information from shower shapes, track quality, and track-cluster matching, is used for identification. The ‘Medium‘ working point is chosen to provide a high signal efficiency with strong rejection of jets misidentified as electrons.
- **Purity:** Similar to muons, cuts on the impact parameters are applied to ensure electrons originate from the primary vertex: $|d_0/\sigma(d_0)| < 5$ and $|z_0 \cdot \sin(\theta)| < 0.5$ mm.
- **Isolation:** The ‘FixedCutPflowLoose‘ isolation working point, defined in a cone of $\Delta R = 0.2$, is required to reject non-prompt electrons and ensure they are well-separated from other particles.
- **Quality Veto:** For the 2015-2016 data-taking period, events containing an electron in a known problematic region of the electromagnetic calorimeter crack

($1.37 < |\eta| < 1.52$) are vetoed to prevent mismeasurement of the event's missing transverse momentum.

Electron energy scale and resolution corrections, as well as efficiency scale factors, are applied to the simulation to ensure accurate modeling of the detector performance. A "baseline" electron selection ($p_T > 7$ GeV, 'LooseLHB' identification) is used for veto purposes.

3. Jets

Jets provide crucial information about the hadronic activity in the event and are key to defining the VBS-like signal region.

- **Reconstruction:** Jets are reconstructed from particle-flow objects using the anti-k_T algorithm with a radius parameter of $R = 0.4$.
- **Kinematics and Cleaning:** Jets are selected if they have $p_T > 30$ GeV and $|\eta| < 4.5$. They must also pass the 'Loose' jet cleaning criteria, which are designed to remove spurious jets arising from detector noise or non-collision backgrounds.
- **Pileup Suppression:** To mitigate the impact of additional proton-proton interactions (pileup), jets within the tracker acceptance ($|\eta| < 2.4$) and with $p_T < 60$ GeV must satisfy a requirement on the Jet Vertex Tagger (JVT) discriminant.
- **B-Jet Veto:** To suppress the large background from top-quark pair production, events containing b-jets are vetoed. Jets are identified as b-jets using the 'DL1r' multivariate tagging algorithm. Any event containing a jet within $|\eta| < 2.5$ that passes the 85% efficiency working point is rejected.

4. Overlap Removal

A single detector signature can sometimes be reconstructed as multiple physics objects. To resolve these ambiguities and prevent double-counting, a sequential overlap removal procedure is applied to the baseline object collections. The procedure follows a prescribed hierarchy based on the most likely identity of the shared signature.

1. Jets within $\Delta R < 0.2$ of a selected electron are removed.
2. Electrons that share an ID track with a selected muon are removed.
3. Jets within $\Delta R < 0.2$ of a selected muon are removed if they have few associated tracks, which is characteristic of muons depositing energy in the calorimeter.
4. Finally, any electrons or muons found within a wider cone of $\Delta R < 0.4$ around any surviving jet are removed. This step effectively rejects non-prompt leptons originating from heavy-flavour hadron decays inside jets.

After this procedure, the final signal selections for leptons and jets are applied to the surviving, uniquely identified objects.

4.2.2 Event Selection

With a foundation of calibrated physics objects, the analysis proceeds to the crucial stage of event selection. The goal is to isolate the distinctive signature of $Z \to \ell\ell\nu\nu$ production from an overwhelming background of other Standard Model processes. The final state is characterized by two same-flavour, opposite-sign leptons consistent with the decay of a Z boson, accompanied by significant missing transverse momentum (E_T^{miss}) due to the two neutrinos from the second Z boson's decay, which escape detection.

The primary challenge in this channel is to distinguish the large, genuine E_T^{miss} originating from the invisible Z decay from the fake E_T^{miss} that arises from jet energy mismeasurements and instrumental effects, which is prevalent in the dominant Drell-Yan (Z+jets) background. Therefore, the event selection strategy is centered around stringent requirements on the E_T^{miss} magnitude and its significance. This is complemented by topological requirements that exploit the expected event kinematics, such as the angular separation between the visible Z boson and the E_T^{miss} vector. Furthermore, dedicated vetoes are employed to suppress other key backgrounds, including a b-jet veto to reject top-quark events and a veto on additional leptons to reduce contributions from WZ and $ZZ \to 4\ell$ processes.

The strategy is to build the selection incrementally, applying successive requirements that target the distinct features of the signal while systematically rejecting specific backgrounds. This process culminates in the definition of two primary signal regions (SRs): an *inclusive* SR for the overall cross-section measurement, and a *VBS-like* SR targeting the electroweak production mode.

1. Baseline Event Requirements and Z Boson Candidate

The initial step in the selection process is to identify a viable candidate for the leptonic Z boson decay, $Z \to \ell\ell$. This forms the cornerstone of the event signature.

- **Data Quality and Trigger:** Events are first required to pass standard data quality checks to ensure all detector components were functioning correctly. They must also have fired a single-lepton trigger, which provides the initial, high-efficiency selection of events containing at least one high-p_T electron or muon.
- **Primary Vertex:** A primary vertex with at least two associated tracks is required, ensuring that the event originates from a genuine proton-proton collision.
- **Dilepton Final State:** The core of the selection requires the presence of exactly two signal leptons (as defined in 4.2.1) of the same flavour and opposite charge

(SFOS). To ensure trigger efficiency is high, the leading and subleading leptons are required to have $p_T > 30$ GeV and $p_T > 20$ GeV, respectively. Events containing any additional "baseline" leptons ($p_T > 7$ GeV) are vetoed. This veto is crucial for suppressing backgrounds with three or more real leptons, primarily from WZ and $ZZ \to 4\ell$ production.

- **On-Shell Z Boson:** To select events consistent with a $Z \to \ell\ell$ decay, the invariant mass of the dilepton pair is required to be within a window around the Z boson mass: $80 < m_{\ell\ell} < 100$ GeV. This is a powerful cut that significantly reduces non-resonant backgrounds such as $t\bar{t}$ and WW production.

2. Targeting the Invisible Z Decay and Suppressing Drell-Yan

After identifying a clean, on-shell Z boson candidate, the selection must target the signature of the second Z boson decaying to neutrinos: large missing transverse momentum (E_T^{miss}). The primary challenge here is rejecting the dominant Drell-Yan (Z+jets) background, where large, fake E_T^{miss} can arise from the mismeasurement of jet energies. A series of topological and kinematic cuts are designed specifically for this purpose.

- **Missing Transverse Momentum:** A significant amount of genuine E_T^{miss} is the key feature of the signal. Therefore, a high threshold is placed on its magnitude.
- **Lepton Collimation:** In the signal process, the $Z \to \ell\ell$ boson often has a high transverse momentum, recoiling against the invisible Z boson. This boost causes its decay products to be more collimated. A requirement of $\Delta R(\ell, \ell) < 1.8$ is applied to exploit this feature, which preferentially rejects Drell-Yan events where the Z boson typically has lower p_T.
- **Topological Correlation:** In signal events, the visible Z boson and the invisible neutrinos are expected to be produced back-to-back in the transverse plane. This results in a large azimuthal separation between the dilepton momentum vector and the E_T^{miss} vector. A cut of $\Delta\Phi(Z, E_T^{\text{miss}}) > 2.2$ is imposed to select events with this topology, strongly suppressing Z+jets events where fake E_T^{miss} from a mismeasured jet is often not aligned opposite to the Z boson.
- **E_T^{miss} Significance:** To further distinguish genuine E_T^{miss} from instrumental effects, the ratio of the missing transverse momentum to the scalar sum of the transverse momenta of all selected objects, H_T, is used. For signal events, a large fraction of the total energy is invisible. A requirement of $E_T^{\text{miss}}/H_T > 0.65$ effectively rejects events with high hadronic activity where the E_T^{miss} is small relative to the total visible energy.

- **B-Jet Veto:** The production of top-quark pairs ($t\bar{t}$) is a significant background, as it can produce two leptons and genuine E_T^{miss} from W boson decays. This background is effectively suppressed by vetoing any event that contains one or more b-tagged jets.

3. Signal Region Definitions

The selection criteria described above were optimized to maximize signal significance and are now combined to define the two signal regions for the analysis.

（1） Inclusive Signal Region

This region is designed to measure the total ZZ production cross-section in this final state. It applies all the selection criteria developed above. The defining requirement on the missing transverse momentum is:

- $E_T^{\text{miss}} > 110$ GeV.

（2） VBS-like Signal Region

This region is tailored to enhance the contribution from electroweak ZZ production in association with two jets (a signature of Vector Boson Scattering). It builds upon the inclusive selection but requires a more energetic and hadronic final state.

- The missing transverse momentum requirement is tightened to $E_T^{\text{miss}} > 150$ GeV to select more energetic events characteristic of VBS.
- A requirement of at least two jets is imposed, with the leading and subleading jets required to have $p_T > 30$ GeV. This explicitly selects the desired ZZ+2-jets topology.

The specific cut values for all variables were chosen following an optimization procedure aimed at maximizing the expected signal significance.

4. Fiducial Phase Space Definition

The ultimate goal of this analysis is to measure the ZZ production cross-section. However, a detector-level measurement is inherently **convolved with** the detector's response, its geometric acceptance, and the efficiencies of the reconstruction and selection algorithms. To unfold these effects and present a result that can be directly compared with theoretical calculations, the measurement is performed within a well-defined **fiducial phase space**.

Defining this fiducial volume is a critical step that serves two main purposes. First, it provides a model-independent measurement target. By restricting the measurement to a phase space accessible to the detector, we minimize the reliance on theoretical models to extrapolate into regions with no experimental sensitivity, thereby reducing the associated theoretical uncertainties. Second, it provides the necessary framework for calculating the correction factors that relate the observed number of events at the detector level to the true number of events produced in the collisions.

The fiducial volume is defined using particle-level (”truth”) kinematics from the Monte Carlo event generator. The selection criteria are chosen to be close to the reconstruction-level requirements but are intentionally relaxed. This ensures that the detector-level selection is fully contained within the fiducial volume, which provides a stable basis for calculating the selection efficiency and minimizes migrations at the selection boundaries. For this analysis, the requirements on the missing transverse momentum and the dilepton invariant mass are notably relaxed at the truth level.

(1) Truth Object Definitions

Before defining the event selection, the particle-level objects are constructed as follows:

- **Dressed Leptons:** To account for final-state QED radiation, the four-momenta of all prompt photons within a cone of $\Delta R(\ell, \gamma) < 0.1$ around a prompt electron or muon are added to the lepton’s four-momentum. This procedure creates ”dressed” leptons, which provide a more realistic proxy for the energy measured in the electromagnetic calorimeter.
- **Truth Neutrinos:** The truth missing transverse momentum ($E_T^{\text{miss, truth}}$) is calculated as the magnitude of the vector sum of the transverse momenta of all prompt neutrinos in the event.
- **Truth Jets:** Jets are clustered from all stable final-state particles (excluding the dressed leptons and all neutrinos) using the anti-k_T algorithm with a radius parameter of $R = 0.4$.

(2) Fiducial Selection for Inclusive Production

For the inclusive $ZZ \to \ell\ell\nu\nu$ cross-section measurement, the fiducial volume is defined by the following requirements on the truth-level objects:

- Exactly two same-flavour, opposite-sign (SFOS) dressed leptons with $|\eta^{\ell}| < 2.5$.
- Lepton transverse momenta of $p_T^{\ell} > 30$ GeV for the leading and $p_T^{\ell} > 20$ GeV for the subleading lepton.
- The dilepton invariant mass must be within the range $76 < m_{\ell\ell} < 106$ GeV.
- The truth missing transverse momentum must be $E_T^{\text{miss, truth}} > 95$ GeV.
- The dilepton angular separation must be $\Delta R(\ell, \ell) < 1.8$.
- The azimuthal separation between the dilepton system and the missing momentum must be $\Delta\Phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss, truth}}) > 2.2$.
- The ratio of missing to total transverse momentum must be $E_T^{\text{miss, truth}}/H_T^{\text{truth}} >$

0.65.

(3) Fiducial Selection for VBS-like Production

For the $ZZjj \to \ell\ell\nu\nu jj$ cross-section measurement, the fiducial volume builds upon the inclusive selection with additional requirements on the hadronic activity:

- All inclusive fiducial selection criteria are applied, with the exception of the truth missing transverse momentum, which is tightened to $E_T^{\text{miss, truth}} > 130$ GeV.
- The event must contain at least two truth jets with $p_T > 30$ GeV and $|\eta| < 4.5$.

(4) Comparison of Detector-Level and Particle-Level Selections

To clearly illustrate the relationship between the final signal region definitions and their corresponding fiducial volumes, a detailed comparison of the selection criteria is provided in Tables 4.15 and 4.16. The deliberate relaxation of the particle-level cuts, particularly for $m_{\ell\ell}$ and E_T^{miss}, is highlighted. This strategy ensures that detector resolution effects do not migrate a significant fraction of signal events from inside the reconstructed selection to outside the fiducial volume, which would lead to an unstable efficiency calculation.

Table 4.15 Comparison of selection criteria for the Inclusive Signal Region at detector-level (Reco) and its corresponding particle-level (Truth) fiducial volume. Key differences are highlighted in bold.

Requirement	**Detector-Level (Reco)**	**Particle-Level (Truth)**
Leptons	Exactly 2 SFOS leptons	
Lepton p_T [GeV]	> 30 (lead), > 20 (sublead)	
Lepton $\lvert\eta\rvert$	< 2.5 (μ); < 2.47 (e)	< 2.5 (e, μ)
Electron $\lvert\eta\rvert$ Veto	**Veto** $1.37 < \lvert\eta\rvert < 1.52$	**Not Applied**
Dilepton Mass ($m_{\ell\ell}$) [GeV]	$80 < m_{\ell\ell} < 100$	$76 < m_{\ell\ell} < 106$
Missing E_T (E_T^{miss}) [GeV]	> 110	> 95
Dilepton $\Delta R(\ell, \ell)$	< 1.8	< 1.8
$\Delta\Phi(\vec{p}_T^{\,\ell\ell}, \vec{E}_T^{\text{miss}})$	> 2.2	> 2.2
E_T^{miss}/H_T	> 0.65	> 0.65
b-jet Veto	**Required**	**Not Applied**

Table 4.16 Comparison of selection criteria for the VBS-like Signal Region at detector-level (Reco) and its corresponding particle-level (Truth) fiducial volume. Differences are highlighted in bold.

Requirement	**Detector-Level (Reco)**	**Particle-Level (Truth)**
Inclusive Selection Base	Applied	Applied
Missing E_T (E_T^{miss}) [GeV]	> 150	> 130
Number of Jets ($p_T > 30$ GeV)	≥ 2	≥ 2
Jet $\lvert\eta\rvert$	**Depends on p_T (e.g., < 2.5 or < 4.5)**	< 4.5

The fiducial selections defined here provide the basis for calculating a correction factor, C, which maps the observed detector-level yield to the particle-level fiducial yield. This factor, derived from simulation, corrects the background-subtracted data for detector inefficiencies and resolution-induced migrations. It is calculated as the ratio of the number of simulated signal events passing the full reconstruction-level selection ($N_{\text{reco}}^{\text{MC}}$) to the number of simulated signal events passing the particle-level fiducial selection ($N_{\text{fid}}^{\text{MC}}$):

$$C = \frac{N_{\text{reco}}^{\text{MC}}}{N_{\text{fid}}^{\text{MC}}}$$

The fiducial cross-section, σ_{fid}, is then determined by:

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L}} \cdot \frac{1}{C}$$

where N_{obs} is the observed number of events in the signal region, N_{bkg} is the estimated background contribution, and $\mathcal{L}$ is the integrated luminosity. This approach isolates the detector-dependent corrections (C) from any model-dependent extrapolations to the full phase space, which are not part of this measurement.

4.3 Background Estimation

In the measurement of the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ cross-section, several background processes contribute. These can be categorized as follows:

- **Irreducible Backgrounds**
  - **Diboson processes:**
    * $WW \to \ell\nu\ell\nu$: The two neutrinos contribute to the MET signature, faking the $ZZ \to \ell\ell\nu\nu$ process.
    * $WZ \to \ell\nu\ell\ell$: If one lepton from the Z is missing, this process could fake the signal.
    * $ZZ \to \ell\ell\ell\ell$: If two leptons escape detection, this process contributes as a background.
- **Reducible Backgrounds**
  - **Top-quark backgrounds:**
    * $t\bar{t}$: If b-jets in the $t\bar{t}$ final states are not tagged properly, it may fake the signal.
    * Single top (tW): Can contribute similarly.
  - **Drell-Yan + jets** ($Z \to \ell\ell$ + jets): Jet energy mismeasurement can lead to artificial MET.
  - **W + jets**: A single W boson decaying leptonically with jets can mimic the signal region due to fake MET.

To achieve precise cross-section measurements, these backgrounds must be carefully estimated and subtracted using control regions. Considering the final states of the backgrounds, they can be categorized as following Control Regions(CR).

- **Non-Resonant Backgrounds (Diboson and Top processes without a Z boson)**
  - $WW \to \ell\nu\ell\nu$: The two neutrinos contribute to the MET signature, faking the $ZZ \to \ell\ell\nu\nu$ process.
  - $t\bar{t} \to WbWb \to \ell\nu b\ell\nu b$: If b-jets are not tagged properly, it may fake the signal.
  - Single top (tW): Can contribute similarly.
- **Non-Resonant + 1b-Jet Backgrounds (Top backgrounds with a b-jet)**
  - $t\bar{t} \to WbWb \to \ell\nu b\ell\nu b$: Events with one identified b-jet contribute to this category.
- **3L Backgrounds (Processes with three leptons in the final state)**
  - $WZ \to \ell\nu\ell\ell$: If one lepton from the Z is lost, this process mimics the

signal.

- **Z+Jets Backgrounds (Processes with a Z boson and jets)**
  - **Drell-Yan + jets** ($Z/\gamma^* \to \ell\ell$ + jets): If jets are mismeasured, they create fake MET.
  - **W + jets**: A single W boson decaying leptonically with jets can mimic the signal region due to fake MET.
- **Instrumental Backgrounds (Detector-related effects)**
  - **Fake MET from mismeasured jets:** Jet energy mismeasurement can lead to artificial MET.
  - **Cosmic-ray muons or beam halo:** Rare cases where fake leptons or MET appear in the detector.

To accurately estimate these background contributions, control regions (CRs) are defined, each enriched with a dominant background category. A simultaneous fit is performed across all CRs and the signal region to constrain both the yields and shapes of these backgrounds. This fit takes event distributions as input and derives scale factors to adjust Monte Carlo (MC) predictions to match data in the CRs. The scaled MC predictions then provide the background estimates in the signal region, ensuring a reliable determination of the differential cross-section.

To further refine background estimation, each control region is designed to enhance a specific type of background, allowing us to isolate and constrain individual contributions effectively. The simultaneous fit across all CRs and the signal region ensures a consistent estimation of background yields and shapes. By utilizing event distributions, this fit derives scale factors that adjust MC predictions to align with data in all CRs. These scaled MC predictions then serve as the background estimates in the signal region, providing a foundation for an accurate differential cross-section measurement.

The following sections describe the estimation strategy for each control region in detail.

4.3.1 Non-Resonant with/without 1 b-jet)

Considering the high percentage of the non-resonant backgrounds, it would be better if Control Regions are well defined to control the backgrounds from MC estimations. Therefore, 2 Control Regions are defined to further estimate the yields from those processes.

One is the non-resonant background, whcih requires Opposite Flavor Opposite Sign(OFOS) leptons in the final state. For example, in the $WW \to \ell\nu\ell\nu$ process, the observable final state could be either Same Flavor Opposite Sign(SFOS) leptons, which fakes the true signals, or Opposite Flavor Opposite Sign(OFOS) leptons. Considering that there is an equal chance for W boson decaying to electron or muon or tau, the yield ratio between SFOS and OFOS final states would be 1:2. Since the OFOS events are well seperated from the SFOS, this would be a good approach to estimate the background yields in Signal Region(SR) using the CR events.

However, since the final state from top quark pair or single top decay contains 1 or 2 b jets, the observed final state could contain 1 or more b jets. Therefore define a CR with 1 b jet to further estimate the yield from the top backgrounds. This non-resonant with a b-jet CR defination is the same as the common non-resonant CR, except the b-jet number requirement.

Since this is aimming to estimate the yields in the SR, the non-resonant background definition is the same as the SR, except requiring the OFOS events. the detailed definations of non-resonant with/without 1 b-jet are shown in the following table.

This is a table TBA

4.3.2 3l

4.3.3 Z+jet

4.3.4 Others

4.4 Systematic Uncertainty

4.5 Unfolding

4.6 DNN Optimization

4.7 Results

Chapter 5 Search for Dark Matter with $ll + E_T^{miss}$ Final State

5.1 Event Selection

5.2 Background Estimation

5.3 Systematic Uncertainty

5.4 Results

Chapter 6 Hardware Work in ATLAS

6.1 sMDT tube construction

6.1.1 sMDT tube Assembly

6.1.2 sMDT tube Quality Test

1. Straightness
2. Gas Tightness
3. Dark Current
4. Tension

6.2 sMDT Chamber Construction

6.2.1 Chamber Assembly

1. Jigging Setup
2. Dark Current

6.2.2 Chamber Quality Test

1. End-cap Measurement
2. Dark Current
3. Cosmic-Ray Test

Chapter 7　Summary

Bibliography

[1] SJOSTRAND T, ASK S, CHRISTIANSEN J R, et al. An introduction to PYTHIA 8.2[J/OL]. Comput. Phys. Commun., 2015, 191: 159-177. DOI: 10.1016/j.cpc.2015.01.024.

[2] BOTHMANN E, CHUMAKOV G, SCHÖNHERR M, et al. Event Generation with Sherpa 2.2 [J/OL]. SciPost Physics, 2019, 7: 034. DOI: 10.21468/SciPostPhys.7.3.034.

[3] AGOSTINELLI S, et al. GEANT4: A Simulation toolkit[J/OL]. Nucl. Instrum. Meth. A, 2003, 506: 250-303. DOI: 10.1016/S0168-9002(03)01368-8.

[4] ATLAS Collaboration. The public ATLAS masterclass dataset from the 13 TeV run of 2016[R]. Geneva: CERN, 2016.

[5] BALL R D, et al. Parton distributions with LHC data[J/OL]. Nucl. Phys. B, 2013, 867: 244-289. DOI: 10.1016/j.nuclphysb.2012.10.003.

Appendix A　Appendix

A.1　Appendix

Acknowledgements

From Template: 在研究学习期间，我有幸得到了三位老师的教导，他们是：我的导师，中国科大 XXX 研究员，中科院 X 昆明动物所马老师以及美国犹他大学的 XXX 老师。三位深厚的学术功底，严谨的工作态度和敏锐的科学洞察力使我受益良多。衷心感谢他们多年来给予我的悉心教导和热情帮助。

感谢 XXX 老师在实验方面的指导以及教授的帮助。科大的 XXX 同学和 XXX 同学参与了部分试验工作，在此深表谢意。

Publications

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