

Precise Test of Standard Model and Search for Anomalous Neutral Triple Gauge Couplings in $Z\gamma$ final states with ATLAS Experiment and Probe of New Physics at CEPC

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Thesis defended at Shanghai, on September 12, 2024

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上海交通大学博士学位论文

在 ATLAS 实验上通过 Z 和光子末态精确检验
标准模型并探索三中性规范反常耦合及其在
CEPC 上的新物理寻找潜力

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申 请 学 位: 理学博士

2024 年 9 月 23 日

**A Dissertation Submitted to
Shanghai Jiao Tong University for Doctoral Degree**

**PRECISE TEST OF STANDARD MODEL AND
SEARCH FOR ANOMALOUS NEUTRAL TRIPLE
GAUGE COUPLINGS IN $Z\gamma$ FINAL STATES WITH
ATLAS EXPERIMENT AND PROBE OF NEW
PHYSICS AT CEPC**

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September 23rd, 2024

上海交通大学

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摘 要

作为粒子物理学中一个至关重要且坚实的理论框架，标准模型 (Standard Model) 界定了基本粒子以及其通过强相互作用力，弱相互作用力和电磁相互作用力的相互作用机制。规范玻色子作为标准模型中不可或缺的组成部分，其特征是自旋为整数，这些规范玻色子包括传递电磁相互作用的光子，作为弱相互作用传播子的 W 和 Z 玻色子，以及负责强相互作用的胶子。这一理论模型还将基本粒子分类为三代费米子，每一代都由特定类型的夸克和轻子组成。希格斯玻色子，作为标准模型中的关键一环，不仅赋予其他粒子质量，同时还在电磁力与弱力之间起到了关键的区分作用。除此之外，任何与标准模型预言之间存在的偏差，都可能是新物理存在的信号。为了寻找新物理的存在，通过构建标准模型有效场理论 (Standard Model Effective Field Theory) 这一框架来寻找任何可能存在的新物理现象。这一框架将更高维度的算符纳入标准模型拉格朗日量中，提供了一种独立于某种特定模型的方法来检验除标准模型之外的新的相互作用，如中性三玻色子反常耦合等，从而加深我们对于宇宙基本结构以及存在机制的理解。

本论文的主要聚焦于对于标准模型过程 $Z\gamma$ 及喷注相关的精确测量，以及基于该过程的新物理寻找。在大型强子对撞机 (the Large Hadron Collider) 上进行 $Z\gamma$ 过程的精确测量，对于加深我们对标准模型的理解以及探索除标准模型以外的潜在新物理信号至关重要。首先，这些精确测量主要集中与量子色动力学 (Quantum Chromodynamics) 辐射相关的色单态产生，从而提升对与强子相互作用的灵敏度。通过分析测量 $Z\gamma$ 事例中 Z 玻色子衰变称为双带电轻子的喷注活动和动力学分布，利用不变质量从而区分初态辐射 (Initial State Radiation) 和末态辐射 (Final State Radiation)。这一测量结果，使得我们能够以较高的精度检验标准模型并且为寻找超出标准模型预言的潜在新物理提供了更过的可能性，如类轴子粒子 (Axion-Like Particle) 或三中性玻色子反常耦合 (neutral Triple Gauge Couplings)。

在先前的测量基础上，本论文的第二个重点是在 ATLAS 探测器中寻找三中性玻色子反常耦合，以此增进我们对于电弱动力学的理解。基于现有的理论框架，三中性玻色子反常耦合现象并不会在 4 维或者 6 维尺度下存在，而是通过引入标准模型有效场理论八维尺度首次出现，这一框架为研究超出标准模型的新物理现象提供了另一途径。此外，该研究通过 $Z\gamma$ 产生机制，其中 Z 玻色子衰变成一对带电轻子，来寻找该反常耦合。通过分析 2015 至 2018 的实验数据 (总积分亮度为 140 fb^{-1} ，能量为

13 TeV)，同时采用探测器效应修正方法测量光子的横向动量分布，并且根据有效场理论得到最新的实验限制结果。这一理论被整合在标准模型有效场理论框架中，不仅优化了对于八维算符的测量，还尝试寻找超出标准模型的潜在新物理信号，从而揭示新物理现象并且进一步拓展对于粒子相互作用的理解。

本论文的最后一部分进一步讨论了在未来轻子对撞机上寻找三中性玻色子反常耦合的研究结果。通过测量正负电子对撞机（the Circular Electron Positron Collider）上 $e^+e^- \rightarrow Z\gamma$ （其中 $Z \rightarrow \ell^+\ell^-$ ）来寻找三中性玻色子反常耦合现象，并给出实验限制。通过分析质心能量为 240 GeV 以及总积分亮度为 20 ab^{-1} 的实验数据，从而得到由八维算符产生的新物理现象的实验限制，进一步延展到与八维算符相关的形状因子（Form Factor）的限制结果。与强子对撞机相比，轻子对撞机如 CEPC，提供了一个本底干扰更少的实验环境，极大的提高了对于超出标准模型过程寻找的精确度。这不仅能够检验标准模型，还进一步测量并寻找了由更高维度产生的相互作用，从而揭示粒子物理的新现象或新相互作用。这些测量也可能加深对于电弱对称性破缺机制的理解，并为理解宇宙内力的统一提供可能性。

综上，本篇论文详细讨论并介绍了 $Z\gamma$ 过程的精确测量结果以及基于该过程的新物理寻找。通过分析不同对撞环境的实验数据，研究并探索电弱相互作用和测量潜在的新物理相互作用，增进了我们对于标准模型的理解。该研究为探索粒子物理领域及研究基本相互作用方面奠定了基础，为进一步拓展粒子物理学的发展铺平了道路。

关键词：高能物理，对撞机，电弱，Z 玻色子，光子，三中性玻色子反常耦合

ABSTRACT

The Standard Model (SM) of particle physics serves as a robust theoretical framework that delineates the fundamental particles and their interactions. These interactions are mediated by three types of forces including : electromagnetic, weak, and strong forces. Gauge bosons are integral components of the SM, characterized by integer spin values. These gauge bosons include the photon, which mediates electromagnetic interactions, the W and Z bosons responsible for weak interactions, and the gluon mediates the strong forces. It also categorizes elementary particles into fermions across three generations, each generation characterized by specific types of quarks and leptons. The Higgs boson, key to the SM, imparts mass to other particles and plays a crucial role in differentiating the electromagnetic and weak forces. To explore potential deviations from the SM and search for new physics, the Standard Model Effective Field Theory (SMEFT) has been developed. This framework incorporates higher-dimensional operators into the SM Lagrangian, providing a model-independent approach to examine new interactions or phenomena beyond the SM, such as neutral Triple Gauge Couplings (nTGCs), thereby enhancing our understanding of the fundamental structure of the universe.

The first focus of this dissertation is the precise measurement of $Z\gamma$ production associated with jets within the SM. Precision measurements of $Z\gamma$ production at the LHC are crucial for advancing our understanding of the SM and exploring potential new physics beyond the SM. These measurements, focusing on color singlet production associated with Quantum Chromodynamics (QCD) radiation, enhance sensitivity to hadronic activity. By analyzing jet activity and kinematic distributions, particularly in $Z\gamma$ events where the Z boson decays into charged leptons by differentiating the contributions from Initial State Radiation (ISR) and Final State Radiation (FSR) on invariant mass distributions, it is possible to test SM predictions with high accuracy and to explore new physics such as Axion-like particles (ALP) or neutral Triple Gauge Couplings (nTGCs). Additionally, the precise measurements help add depth to our understanding of Standard Model physics.

Advancing previous measurements, the second focus of this dissertation explores neutral Triple Gauge Couplings (nTGCs) at the ATLAS detector, enhancing our understanding of electroweak dynamics. The nTGCs are absent at dimension-6 and only emerge at

dimension-8 within the framework of the SMEFT, presenting a distinctive path for investigating phenomena beyond the SM. This study also concentrate on the $Z\gamma$ production where the Z boson decays into pair of charged leptons, utilizing data from 2015 to 2018 with an integrated luminosity of 140 fb^{-1} at 13 TeV. An advanced statistical method is employed to analyze photon transverse momentum distributions, and helps to extract the exclusion constraints based on effective field theory, which is integrated within the SMEFT framework. This approach not only refines the measurements of dimension-8 operators but also attempts to detect potential deviations from the SM. Additionally, revealing new physics phenomena and offering a more comprehensive understanding of particle interactions within the SMEFT framework in a model-independent way.

The concluding focus of this dissertation extensively explores the search for neutral Triple Gauge Couplings (nTGCs) at a future lepton collider. This analysis studies nTGCs through the reaction of $e^+e^- \rightarrow Z\gamma$ with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) at the Circular Electron Positron Collider (CEPC). Employing a center-of-mass energy of $\sqrt{s} = 240\text{ GeV}$ with an integrated luminosity of 20 ab^{-1} , the study assesses sensitivities to new physics scales related to dimension-8 nTGC operators. The form factors corresponding to these operators are dedicatedly evaluated through the comprehensive detector-level simulation. The use of a lepton collider, such as CEPC, provides a cleaner experimental environment with less background contributions compared to hadron colliders, greatly enhancing the precision in searches for BSM phenomena. This search not only tests the boundaries of the SM but also probes the interactions that manifest at higher dimensions, potentially revealing new phenomena of particle physics. These measurements could also provide critical insights into the electroweak symmetry breaking mechanism and offer a possibility to further understand the unification of forces within the universe.

This dissertation presents a detailed examination of $Z\gamma$ production, focusing on precise measurements and the exploration of new phenomena across both hadron and lepton colliders. This study enhances our understanding of the SM by probing the electroweak interactions and identifying potential new physics interactions. By integrating data from diverse collider environments, the research contributes significantly to the broader field of particle physics, paving the way for future discoveries in fundamental interactions.

Key words: High Energy Physics, Collider, Electroweak, Z boson, Photon, Neutral Triple Gauge Couplings

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Chapter 1 Introduction

The Standard Model (SM) of particle physics is an elegant and well-established theory that describes the fundamental forces and particles in the universe. It offers a detailed theoretical framework explaining the interactions of fundamental particles mediated by gauge bosons that include the photon, W and Z bosons, and gluons, corresponding to electromagnetic, weak, and strong forces, respectively. It categorizes elementary particles into fermions and bosons, highlighting the crucial role of the Higgs boson, which confers mass to particles and solidifies the model foundation. Despite its extensive success in describing numerous physical phenomena, the Standard Model falls short in addressing gravity, dark matter, dark energy, and the mass origins of neutrinos, which underscores its inherent limitations.

Building on the fundamental principles of the Standard Model, this research focuses on the $Z\gamma$ production channel. This channel is particularly chosen for its distinct advantages in probing new physics phenomena beyond the established framework, including neutral Triple Gauge Couplings (nTGCs). $Z\gamma$ production is notably favorable due to its clean experimental signature and the abundant production rate at colliders, which enable precise measurements and provide a robust dataset for analysis. Additionally, the presence of a Z boson decaying leptonically offers a clear final state with small background contributions. This makes it an excellent probe for testing the SM predictions and for observing potential deviations indicating the existence of nTGCs.

The research began with precise measurements of $Z\gamma$ production in association with jets activity at the Large Hadron Collider (LHC). Specifically, this study focused on determining both the integrated and differential cross sections for $Z\gamma$ production, crucial for understanding the electroweak gauge boson interactions. This effort was crucial, as it not only solidified our understanding of gauge boson interactions under the SM but also provided a fertile ground for detecting subtle deviations that could indicate the presense of nTGCs. These measurements are vital for testing the accuracy of the Standard Model and for opening windows into new physics through potential discrepancies observed in $Z\gamma$ +jets cross section measurements.

Following the detailed measurements on differential cross sections of $Z\gamma$ +jets production, the research transitions into probing new physics phenomena beyond the Standard Model, specifically targeting neutral Triple Gauge Couplings (nTGCs). The nTGCs, which are absent

with the Standard Model predictions, potentially arise within the framework of the Standard Model Effective Field Theory (SMEFT) when exploring higher-dimensional operators. The precise measurements on cross sections in the $Z\gamma$ +jets channel serve as a foundational layer, setting the stage for detailed studies into the potential existence of nTGCs. The ability to detect subtle deviations in this channel provides a direct pathway to investigate interactions that may arise from dimension-8 operators in SMEFT, offering insights into phenomena beyond conventional gauge boson interactions.

The exploration of nTGCs is further extended to lepton colliders, such as the Circular Electron Positron Collider (CEPC). The lepton collider, compared to a hadron collider, offers a cleaner experimental environment that improves measurement sensitivities and precision. Moreover, it allows for more accurate $Z\gamma$ production measurements, essential for investigating electroweak symmetry breaking and potentially new phenomena beyond the SM. This multi-faceted study, starting with rigorous measurements at the LHC, and then extending to innovative searches at lepton colliders, is driven by the overarching goal to meticulously test the limits of the Standard Model and illuminate new areas where physics beyond the Standard Model might manifest. By integrating advanced theoretical models with empirical data from diverse collider environments, this research not only aims to confirm or test the Standard Model predictions but also to uncover and characterize potential new interactions that could fundamentally alter our understanding of particle physics.

The structure of this dissertation is organized as follows :

- **Chapter 2** Presents an overview of the Standard Model theory and beyond.
- **Chapter 3** Introduces the Large Hadron Collider and the ATLAS experiment.
- **Chapter 4** Provides an introduction of event simulation and object reconstruction in the ATLAS experiment.
- **Chapter 5** Documentation on precise measurements of $Z\gamma$ +jets productions.
- **Chapter 6** Documentation on searching for neutral triple gauge couplings in the ATLAS experiment.
- **Chapter 7** Documentation on exploring for neutral triple gauge couplings at future lepton colliders.
- **Chapter 8** Summarizes the measurements and discussions for future prospects.

Chapter 2 The Standard Model Physics and Beyond

The Standard Model (SM)^[1] of particle physics is a robust theoretical framework that describes the fundamental particles and their interactions via three forces: the electromagnetic force mediated by photons, the weak force by W and Z bosons^[2-4], and the strong force by gluons. The model classifies elementary particles into fermions, divided into quarks and leptons across three generations. Each generation includes two types of quark (up-type and down-type) and two types of leptons (one charged and one neutral neutrino). The Higgs boson, integral to the model, imparts mass to other particles and distinguishes between the electromagnetic and weak forces.

To extend the SM, the Standard Model Effective Field Theory (SMEFT)^[5-8] framework has been developed. SMEFT incorporates higher-dimensional operators into the SM Lagrangian, enabling a systematic approach to explore deviations from the SM predictions and probe potential new physics beyond the SM^[9], such as neutral triple gauge couplings (nTGCs)^[10-14]. It provides a model-independent methodology to analyze and interpret possible new interactions beyond the SM, allowing for a comprehensive exploration of new physics to uncover subtle signs of new phenomena within the fundamental structure of matter.

2.1 Introduction to Fundamental Particles

The Standard Model (SM) classified elementary particles into two primary categories: fermions and bosons, each with distinct characteristics and roles within the cosmos, as illustrated in Fig. 2-1.

Fermions Serving as the fundamental constituents of matter, fermions are subject to the Pauli Exclusion Principle, which prohibits them from occupying identical quantum states simultaneously. Fermions, which possess half-integer spins, are divided into quarks and leptons.

- **Quarks** There are six types of quarks: up, down, charm, strange, top, and bottom. The up, charm, and top quarks possess a fractional electric charge of $+2/3$, whereas the down, strange, and bottom quarks have a charge of $-1/3$. Quarks are unique in their

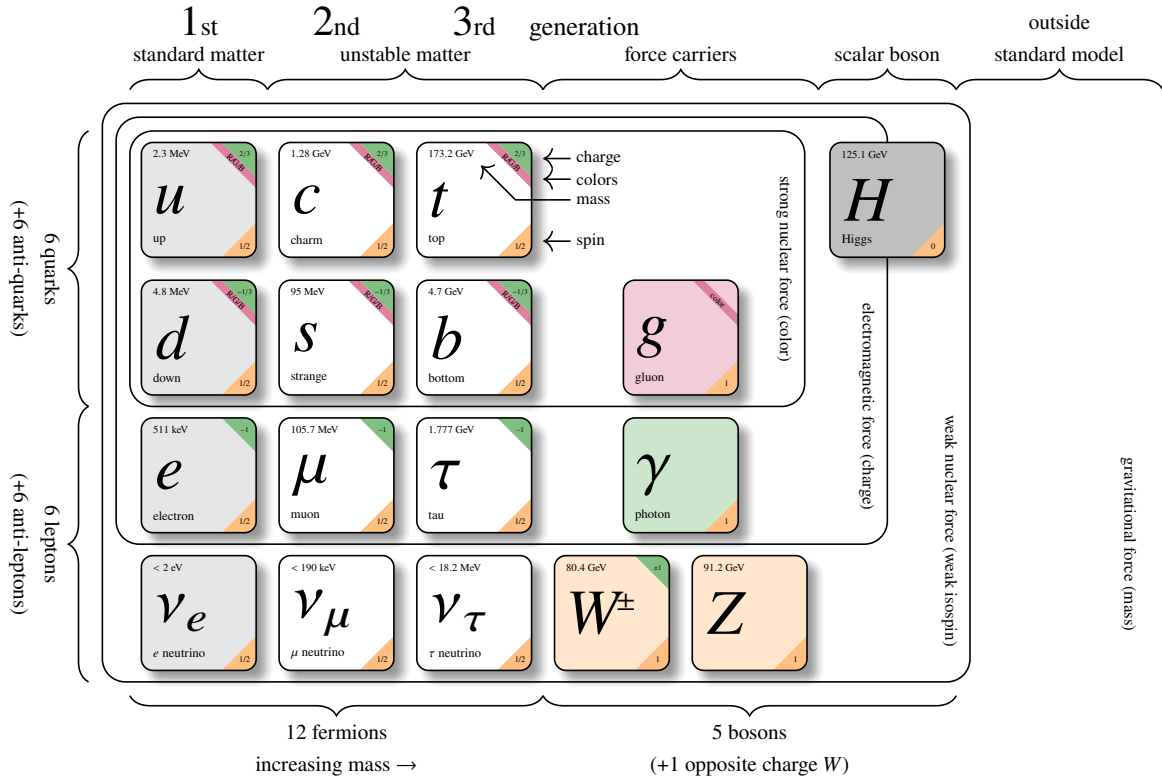


Figure 2-1 Properties of elementary particles within the Standard Model.

interaction with all three fundamental non-gravitational forces: strong, weak, and electromagnetic. They also exhibit a property known as "color charge", which is essential for their interactions via the strong force. Each quark flavor exists in three color states.

- **Leptons** Leptons are also segmented into six varieties across three generations: electrons, muons, tau particles, and their corresponding neutrinos. All charged leptons, including electrons, muons, and tau leptons, possess a unit negative charge and interact through electromagnetic and weak forces. While these interactions are the most significant at the particle level, leptons also experience gravitational forces as well, though these are exceedingly weak at the scale of fundamental particles.

Bosons These particles act as mediators of the fundamental forces and possess integer spins, which allows multiple bosons to occupy the same quantum state. The recognized bosons within the SM include the photon, W and Z bosons, gluons, all of which are vector bosons with spin. Additionally, the Higgs boson is the scalar boson that does not possess spin.

- **Photon** The photon is the mediator of electromagnetic interactions among electrically charged particles. It is a massless particle that travels at the speed of light.
- **W and Z Bosons** These bosons facilitate the weak force, responsible for processes such as beta decay. The W bosons are positively or negatively charged, influencing the short-range nature of the weak force, while the Z boson is neutral.
- **Gluons** Gluons are the mediators of the strong force, responsible for binding quarks together within hadrons such as protons and neutrons. Unlike forces that act within the nucleus, the strong force primarily operates at the subnuclear level, maintaining the integrity of hadrons through color charge interactions among quarks.
- **Higgs Boson** Associated with the Higgs field, the Higgs boson arises from the Brout-Englert-Higgs mechanism^[15-17], a fundamental process that imparts mass to particles through the "Yukawa" interactions^[18].

2.2 Introduction to the Standard Model

The Standard Model (SM) represents the cornerstone of contemporary particle physics, delineating the elementary particles and their interactions, with the notable exclusion of gravitational forces. This framework, defined by its non-Abelian characteristics, Lorentz invariance, and gauge invariances, has been developed progressively since the 1960s. Over the decades, the Standard Model has consistently validated numerous experimental observations with exceptional accuracy.

The theoretical foundation of the SM is constructed around the symmetry group $SU(3) \times U(2) \times U(1)$. Within this structure, $SU(3)$ is responsible for the dynamics of the strong nuclear interaction, while $SU(2) \times U(1)$ orchestrates the electroweak interactions. The Lagrangian of the Standard Model is succinctly formulated as follows:

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} \quad (2-1)$$

In this expression, $\mathcal{L}_{EW}$ represents the Lagrangian for electroweak interactions, and $\mathcal{L}_{QCD}$ pertains to the quantum chromodynamics sector.

2.2.1 The Gauge Principle and the Lagrangian of the Standard Model

The Standard Model (SM)^[19] is fundamentally structured on the principles of gauge theory, which posits that the fundamental interactions between elementary particles are manifestations of the symmetries of the Lagrangian under local gauge transformations. The analysis begins by considering the symmetries of a Lagrangian for free particles under global transformations and subsequently extending these to local symmetries.

Consider, as an example, the Dirac Lagrangian density for an unbound electron or positron:

$$\mathcal{L}_{\text{free}} = \bar{\psi}_e (i\gamma^\mu \partial_\mu - m_e) \psi_e = i\bar{\psi}_e \gamma^\mu \partial_\mu \psi_e - m_e \bar{\psi}_e \psi_e \quad (2-2)$$

Here, ψ_e represents the fermionic field for the electron, m_e is the mass of the electron, and γ^μ are the gamma matrices connected to the Pauli spin matrices σ^i as detailed:

$$\gamma^0 = \begin{pmatrix} 0 & I_{2 \times 2} \\ I_{2 \times 2} & 0 \end{pmatrix}, \gamma^i = \begin{pmatrix} 0 & \tau^i \\ -\tau^i & 0 \end{pmatrix} \quad (2-3)$$

where τ^i are the Pauli matrices:

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad (2-4)$$

The Dirac Lagrangian features two distinct terms: the first is kinematic term which dictates the dynamics of the fermionic field, and the second is the mass term, invariant under Lorentz transformation. This Lagrangian is invariant under global $U(1)$ phase transformation expressed as:

$$\psi_e \rightarrow \psi'_e = e^{iq\theta} \psi_e \quad (2-5)$$

with θ being a constant phase shift. However, this symmetry is not maintained under local $U(1)$ transformations:

$$\psi_e \rightarrow \psi'_e = e^{iq\theta(x)} \psi_e, \quad (2-6)$$

prompting the introduction of the gauge field A_μ , and the modification of the partial derivative to a covariant derivative:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + iqA_\mu \quad (2-7)$$

And the transformation of A_μ preserves local gauge invariance as:

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu \theta(x) \quad (2-8)$$

The modified Lagrangian now includes the gauge field A_μ , reflecting the interaction between the electromagnetic current and the gauge field:

$$\mathcal{L} = \bar{\psi}_e i \gamma^\mu D_\mu \psi_e \equiv \mathcal{L}_{\text{free}} - q J^\mu A_\mu \quad (2-9)$$

The Lagrangian of the Standard Model encapsulates the dynamics of all known elementary particles and their interactions, excluding gravitational forces. It is structured as follows:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) \quad (2-10)$$

This Lagrangian is comprised of several key components, each reflecting different interaction dynamics^[20]:

- $-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$, the kinematic term for gauge field, describes the field strength tensor $F_{\mu\nu}$, representing the flux of the gauge field. It is fundamental for describing the propagation of force carriers like photons and gluons in spacetime.
- $i \bar{\psi} \not{D} \psi$, this term encapsulates the fundamental interactions among matter particles and gauge bosons, comprising electromagnetic, strong, and weak forces. The electromagnetic forces are conveyed by photons, strong forces by gluons, and weak forces by W and Z bosons. Notably, the weak interaction processes the distinctive capability to alter the type of participating matter particles, facilitating processes such as quark flavor change.
- $h.c.$ this term is the "Hermitian conjugate" of term 2, ensuring that the Lagrangian remains Hermitian, a necessary condition for the physical observables, derived from it to be real, thus preserving the probabilistic interpretation of quantum mechanics.
- $\psi_i y_{ij} \psi_j \phi$, represents the interaction between the matter fermions and the Brout-Englert-Higgs (BEH) field, ϕ . It specifically involves the interaction of quarks and leptons with the Higgs field.
- $h.c.$ this term is the "Hermitian conjugate" of the Yukawa couplings from term 4, accounts for the corresponding interactions but involving antiparticles, which is essential for the theoretical symmetry and completeness of the model.
- $|D_\mu \phi|^2$, the Gauge Boson-Higgs interaction, describes the interaction dynamics between the gauge bosons of the weak force (W and Z bosons) and the BEH field. It is fundamental in explaining how these bosons, unlike photons and gluons, gain mass through the Higgs mechanism.

- $V(\phi)$ this term details the Brout-Englert-Higgs field potential and delineates the interactions of Higgs bosons among themselves.

The formulation of each component within the Lagrangian is governed by the principles of gauge symmetry, special relativity, and quantum mechanics, with parameters (such as particle masses and coupling constants) established through experimental validation. Particle interactions occur through the exchange of gauge bosons: photons mediate electromagnetic forces, while gluons are responsible for strong force interactions. The Higgs field is pivotal within the SM, crucial for the mechanism of spontaneous symmetry breaking that imparts mass to other particles, where the magnitude of interaction with the Higgs field is proportional to their masses. Detailed exploration of the Higgs field and its implications are further discussed in the following sections.

2.2.2 The Electroweak Interactions and the Lagrangian

The concept of electroweak unification in particle physics fundamentally integrates the electromagnetic and weak nuclear forces. This theory, articulated under the symmetry group $SU(2) \times U(1)^{[21]}$, is pivotal to the SM, providing a coherent framework to explain the behavior of elementary particles at high energies. At such energy scales, the electromagnetic force, mediated by photons, and the weak force, mediated by W and Z bosons, are treated as manifestations of a singular electroweak force. This theoretical fusion^[22-24] was initially proposed by Sheldon Glashow, Abdus Salam, and Steven Weinberg, earning them the Nobel Prize in Physics in 1979 due to its profound impact on our understanding of particle interactions.

The Lagrangian of the electroweak interaction^[25], denoted as $\mathcal{L}_{EW}$, comprises several components each representing different interactions and fields:

$$\mathcal{L}_{EW} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\phi} + \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{Yukawa}} \quad (2-11)$$

1. **Gauge Boson Dynamics** $\mathcal{L}_{\text{gauge}}$, the gauge boson component of the Lagrangian, represented as:

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}, \quad (2-12)$$

describes the self-interactions and dynamics of the gauge fields associated with $SU(2) \times U(1)$. Here, $W_{\mu\nu}^i$ and $B_{\mu\nu}$ are field strength tensors that incorporate both the linear and nonlinear dynamics of the gauge fields, crucial for understanding their propagation and interactions.

2. **Higgs Mechanism** Building on the foundation of gauge boson dynamics, the Higgs mechanism further explains the mass generation process underpinning electroweak symmetry breaking. $\mathcal{L}_\phi$, the Higgs sector, expressed as:

$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger D_\mu \phi - V(\phi), \quad (2-13)$$

details the behavior of the Higgs field ϕ , a scalar field responsible for electroweak symmetry breaking. The potential $V(\phi)$, which follows a quartic form, leads to the spontaneous symmetry breaking necessary for the mass generation for the W and Z bosons while keeping the photon massless. The Higgs field imparts mass to the W and Z bosons through the mechanism of spontaneous symmetry breaking, while its non-zero vacuum expectation value transforms the nature of these gauge bosons.

3. **Fermion Interactions** $\mathcal{L}_{\text{fermion}}$, this term covers the interactions of fermions with the gauge fields:

$$\mathcal{L}_{\text{fermion}} = \sum_i \bar{\phi}_L^j i\gamma^\mu D_\mu^L \phi_L^j + \sum_{j,\sigma} \bar{\phi}_{R,\sigma}^j i\gamma^\mu D_\mu^L \phi_{R,\sigma}^j, \quad (2-14)$$

integrating the covariant derivatives that couple fermions to the gauge bosons. This interaction is foundational for the processes where fermions emit or absorb gauge bosons.

4. **Yukawa Couplings** $\mathcal{L}_{\text{Yukawa}}$, the Yukawa interactions as expressed:

$$\mathcal{L}_{\text{Yukawa}} = - \sum_{m,n=1}^F [\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\phi} u_{nR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \tilde{\phi} d_{nR}^0 + \Gamma_{mn}^e \bar{l}_{mn}^0 \phi e_{nR}^0] + h.c. \quad (2-15)$$

are crucial for providing masses to fermions once electroweak symmetry is broken. These couplings between the Higgs field and fermions are vital for the mass acquisition mechanism post the Higgs field acquiring a non-zero vacuum expectation value.

The Lagrangian for the electroweak interaction, $\mathcal{L}_{\text{EW}}$, encapsulates the dynamics and self-interactions of the gauge fields corresponding to these symmetries. However, despite initial predictions that the gauge bosons were massless, the real-world phenomena of the weak force's short range and the massiveness of the W and Z bosons required a novel theoretical adaptation. This necessity brought forth the Brout-Englert-Higgs mechanism, which introduces a complex scalar Higgs field. This field spontaneously breaks the $\text{SU}(2) \times \text{U}(1)$ symmetry down to $\text{U}(1)_{\text{em}}$, the electromagnetic gauge group, thus endowing the W and Z bosons with mass while leaving the photon massless.

This symmetry breaking^[26] is not merely a theoretical construct but has been robustly supported by experimental evidence. The electroweak theoretical predictions were confirmed with the discovery^[3,27-28] of the W and Z bosons at CERN Super Proton Synchrotron in the 1980s, along with further precision measurements at the HERA, LEP, and Tevatron colliders, which demonstrated the unification of charged current and neutral current cross-sections at high squared momentum transfers Q^2 ^[29]. These validations underscore the model accuracy and the critical role of the Higgs field in the mass generation mechanism through symmetry breaking, essential for the distinct characteristics of the weak and electromagnetic forces at lower energies.

In conclusion, the unification of the electromagnetic and weak forces exemplifies the profound symmetry principles of the Standard Model, bridging two fundamental forces at high energy levels and revealing their singular nature above the electroweak scale, approximately 100 GeV. The continued exploration of electroweak unification not only enriches our understanding of the universe at fundamental levels but also sets the stage for future breakthroughs in tackling the unresolved mysteries like dark matter and quantum gravity.

2.2.3 The Higgs Mechanism in Symmetry Breaking

In the Standard Model, the Brout-Englert-Higgs mechanism^[26,30] plays a crucial role by providing a means to reconcile the theoretical requirement for massless gauge bosons under gauge symmetry with the empirical observation that W and Z bosons possess mass. While the gauge boson dynamics set the stage for fundamental particle interactions, the Higgs mechanism builds on this framework by introducing a scalar field responsible for mass generation. This connection is pivotal, as it links the force-carrying capabilities of bosons with the mass properties dictated by the Higgs field.

The Lagrangian of dynamics and Higgs field structure responsible for this process is formulated as follows:

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (2-16)$$

where D_μ denotes the covariant derivative incorporating the W and B gauge fields, which interact with the Higgs field ϕ . This scalar field, expressed as a complex doublet in the SU(2)

space, is represented by:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2-17)$$

where v is the Vacuum Expectation Value (VEV) that quantifies the symmetry-breaking scale, and $h(x)$ represents the physical Higgs boson manifesting as quantum fluctuations about the vacuum.

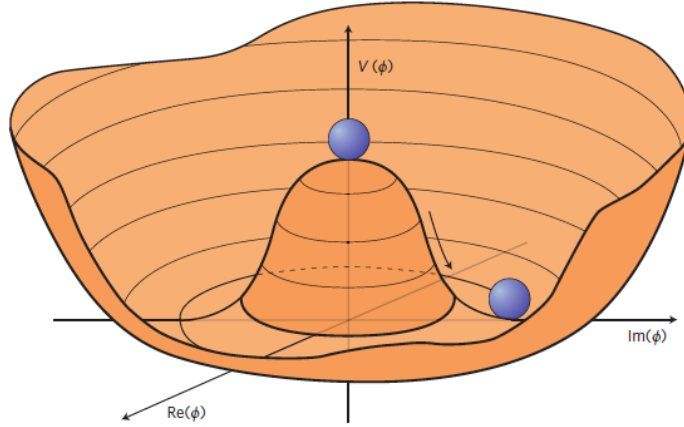


Figure 2-2 The "Mexican hat" potential helps to visualize how particle gain mass^[31]. It suggests that the lowest energy state, or the vacuum, is located not at the center but anywhere along the minimum of the hat. When considering global symmetry, oscillations around this rim correspond to massless particles known as Nambu-Goldstone bosons. However, under local symmetry, these bosons combine with gauge bosons to form massive particles. The Higgs boson, a significant outcome of this mechanism, emerges from specific movements along the rim, representing the mass acquisition process in the field of particle physics.

The potential $V(\phi)$ shaping the Higgs field dynamics is given by:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (2-18)$$

where $\mu^2 < 0$ and $\lambda > 0$. This configuration ensures a stable potential with a spontaneous symmetry-breaking vacuum at $\phi^\dagger \phi = \mu^2/(2\lambda)$, forming the well-known "Mexican hat" potential landscape as illustrated in Fig. 2-2. The non-zero minimum or VEV $v = \sqrt{-\mu^2/\lambda}$ determines the scale at which symmetry is spontaneously broken, transitioning the gauge bosons from a massless to a massive state.

Upon examining the kinematic term $(D^\mu \phi)^\dagger (D_\mu \phi)$ and the potential $V(\phi)$ near the vacuum expectation value, we find terms proportional to $W^\mu W_\mu$, $B^\mu B_\mu$ and h^2 . These terms are

responsible for providing mass to the W and Z bosons, and the Higgs boson, respectively. More specifically, the mass of the Higgs boson is determined to be $m_H = \sqrt{2\lambda v}$, where v represents the VEV of the Higgs field. Here, λ denotes the self-coupling constant of the Higgs field within the Higgs potential, influencing the curvature of the potential at the minimum and playing a critical role in determining the mass of the Higgs boson.

Following symmetry breaking, the gauge bosons W and Z acquire mass directly proportional to the Higgs field VEV:

$$m_W = \frac{g}{2}v, m_Z = \frac{\sqrt{g^2 + g'^2}}{2}v \quad (2-19)$$

derived from their couplings to the Higgs field. Here, g and g'^2 are the gauge couplings corresponding to the SU(2) and U(1) gauge fields, respectively. Additionally, fermion masses are generated via the Yukawa interactions, formulated as:

$$\mathcal{L}_{\text{Yukawa}} = -\frac{y_f v}{\sqrt{2}}\psi_f \bar{\phi}_f - \frac{y_f h}{\sqrt{2}}\bar{\psi}_f \phi_f + h.c. \quad (2-20)$$

the first term in the expression for fermion masses, $m_f = y_f v / \sqrt{2}$, indicates the mass term derived from the non-zero vacuum expectation value (VEV) of the Higgs field, essential for the Higgs mechanism in mass generation. This mechanism ensures that fermions acquire mass proportionally to the VEV of the Higgs field. The subsequent term signifies the interaction between the Higgs boson and fermions, which is scaled by the fermion mass. These interactions are pivotal in both the production and decay processes of the Higgs boson in particle accelerators. Within the SM, the values of the Yukawa couplings y_f are empirically determined, underscoring their significance in particle physics.

The Brout-Englert-Higgs (BEH) mechanism and its consequential spontaneous symmetry breaking constitute core elements of the Standard Model, providing a unified approach to describing the weak nuclear force and electromagnetism and offering a profound explanation for the observed masses of fundamental particles. The mechanism leverages the Higgs field, characterized by a non-zero VEV, which plays a vital role in this process. Instead of actually "breaking" the symmetry, the mechanism effectively "hides" it—while the overarching theory maintains symmetry, the emergent ground state does not exhibit this symmetry. This nuanced approach is critical for our modern understanding of particle physics.

It is essential to highlight that introducing direct mass terms for gauge bosons would contravene gauge invariance, a cornerstone of the Standard Model's symmetry. Gauge in-

variance is a fundamental principle in physics that states the basic laws governing particle interactions do not change under local transformations of the gauge fields. The Higgs mechanism, initiated from a massless theory framework that mandates gauge invariance, introduces effective mass terms post-electroweak symmetry breaking. This sophisticated solution ensures the theory remains consistent and gauge invariant while simultaneously explaining the origin of mass for particles.

2.3 Introduction to Neutral Triple Gauge Couplings

2.3.1 The General Introduction of SMEFT

The Standard Model Effective Field Theory (SMEFT)^[6] is a profound theoretical extension of the Standard Model (SM)^[19] of particle physics, designed to incorporate potential influences from new physics phenomena at higher energy scales. SMEFT modifies the Standard Model by introducing higher-dimensional operators into its Lagrangian, which are constructed to respect the SM gauge symmetries of $SU(3) \times SU(2) \times U(1)$. These operators, typically of dimension six or higher^[32-34], expand the model scope, enabling it to describe interactions that the Standard Model cannot, due to its constraints at the electroweak scale.

Historically, effective field theories originated from studying weak interactions and were further developed through the Fermi theory of four-fermion interactions^[35]. This theoretical approach was pivotal in formulating the exchange of massive bosons, laying the groundwork for the eventual discovery and integration of the W and Z bosons^[2] via the Electroweak Theory, which itself was further substantiated by the Higgs mechanism.

SMEFT is a meticulously designed to explore and potentially validate extensions to the SM through the systematic introduction of new operators. Powers of a scale Λ , associated with new physics, suppress these operators, thus enabling practical, testable predictions within the reach of current and forthcoming experimental technologies. I technologies.

The SMEFT Lagrangian is expressed as^[7] :

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} O_i, \quad (2-21)$$

where Λ is the new physics scale, C_i are the Wilson coefficients, and O_i represents the new higher-dimensional operators. Among these, there are 2499 possible operators in the

dimension-6 part of the SMEFT Lagrangian, reflecting the complexity and the comprehensive nature of potential interactions SMEFT is equipped to explore.

This elaborate framework allows for in-depth studies of deviations from the SM predictions, providing a structured, model-independent way to search for new physics. SMEFT enhances our understanding of the fundamental constituents of matter and their interactions, underpinning ongoing experimental investigations and theoretical developments in particle physics. It continues to be an essential tool for bridging experimental capabilities with the theoretical frontier of high-energy physics, offering insights that could lead to a more complete understanding of the fundamental forces within the universe.

2.3.2 The Neutral Triple Gauge Couplings

Neutral triple gauge couplings (nTGCs)^[10-14] represent an advanced theoretical concept within the framework of the Standard Model Effective Field Theory (SMEFT), which posits interactions among three neutral gauge bosons, such as the photon (γ) or the Z boson. These higher-dimensional interactions, typically emerging at the dimension-8 level or beyond within SMEFT, are key to exploring physics that extend beyond the predictions of the SM. This elevated level of theoretical complexity allows for a refined exploration of interactions that cannot be adequately described by dimension-6 or lower operators within the SM.

nTGCs are characterized by their occurrence in the dimension-8 operators of SMEFT, which indicates that they involve interactions extending beyond the typical gauge boson dynamics forecasted by the SM. These higher-dimensional operators introduce terms that can affect the vertices involving gauge bosons such as the Z bosons and the photon (γ) in ways as illustrated in Fig. 2–3, that are not permissible under the SM dimension-4 terms or even the new physics insights potentially provided by dimension-6 interactions.

The general Lagrangian of nTGCs incorporates dimension-8 operators, highlighting the potential impact on gauge boson interactions can be expressed as:

$$\mathcal{L}_{\text{SMEFT}} = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4} \mathcal{O}_j = \sum_j \frac{\text{sign}(\tilde{c}_j)}{\Lambda_j^4} \mathcal{O}_j = \sum_j \frac{1}{[\Lambda_j^4]} \mathcal{O}_j \quad (2-22)$$

where the dimensionless coefficients $\tilde{c}_j$ associated with each dimension-8 operator $\mathcal{O}_j$ in the SMEFT Lagrangian could be either positive or negative. The effective cutoff scale $\Lambda_j \equiv \tilde{\Lambda}/|\tilde{c}_j|^{1/4}$. Additionally, we denote $[\Lambda_j^4] \equiv \text{sign}(\tilde{c}_j)\Lambda_j^4$.

The key dimension-8 operators relevant to nTGCs include:

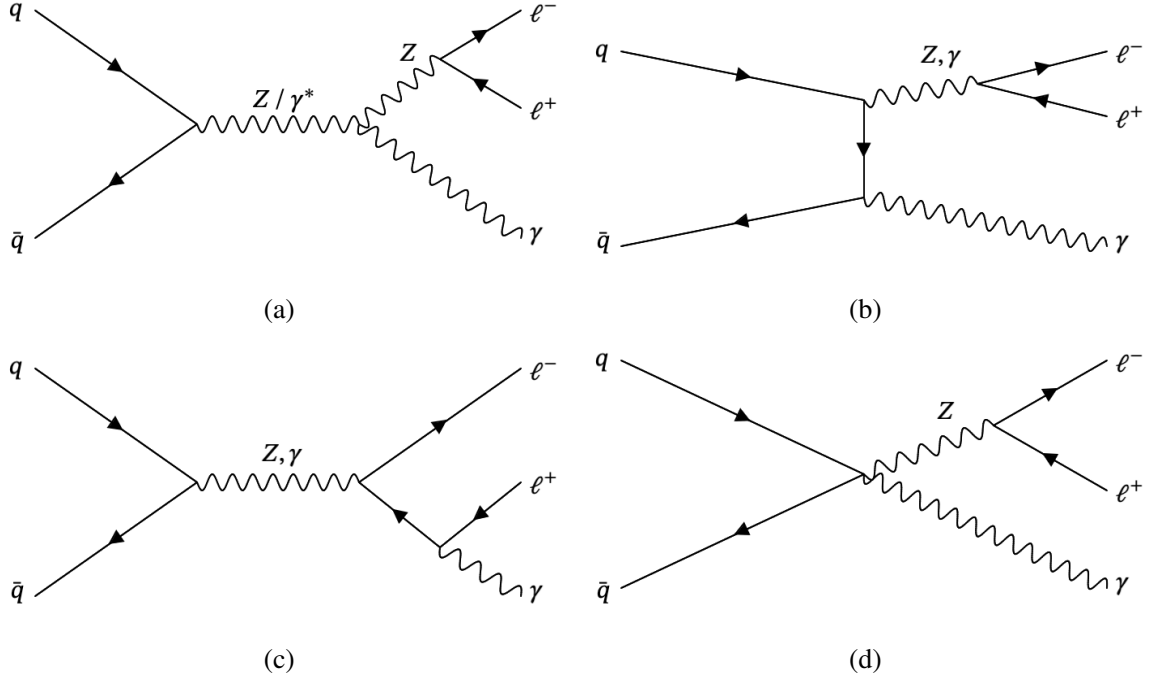


Figure 2-3 Feynman diagrams that contribute to $pp \rightarrow \ell^+ \ell^- \gamma$ reaction.

Diagram a, is particularly significant as it signals the presence of neutral triple gauge couplings (nTGCs) through the vertices like $Z\gamma V^*$, where $V = Z, \gamma$, derived from dimension-8 operators. Diagram b and c, illustrate SM backgrounds : b represents an irreducible background involving a u-channel diagram, while c involves s-channel gauge boson exchange with photon radiation in the final state, constituting a reducible background. Diagram d, emerges from a contact vertex $ppZ\gamma$ which originates from dimension-8 fermion-bilinear operators, further illustrating the complexity of interactions in this reaction^[12].

- O_{G+} , O_{G-} , $O_{\tilde{G}+}$ and $O_{\tilde{G}-}$, involve combinations of the field strength tensors and covariant derivatives, affecting the couplings and dynamics of gauge bosons.

$$gO_{G+} = \tilde{B}_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} + D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (2-23a)$$

$$gO_{G-} = \tilde{B}_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} - D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (2-23b)$$

$$gO_{\tilde{G}+} = B_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} + D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (2-23c)$$

$$gO_{\tilde{G}-} = B_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} - D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (2-23d)$$

- $O_{\tilde{B}W}$, $O_{B\tilde{W}}$, O_{BB} , O_{BW} , and O_{WW} , include interactions between the Higgs boson, gauge bosons, and derivatives, indicating potential modifications to electroweak symmetry

breaking and Higgs mechanics.

$$O_{\widetilde{B}W} = iH^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{H.c.} \quad (2-24a)$$

$$O_{\widetilde{B}\widetilde{W}} = iH^\dagger (D_\sigma \widetilde{W}_{\mu\nu}^\alpha W^{\alpha\mu\sigma} + D_\sigma \widetilde{B}_{\mu\nu} B^{\mu\sigma}) D^\nu H + \text{H.c.} \quad (2-24b)$$

$$O_{BB} = iH^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H + \text{H.c.} \quad (2-24c)$$

$$O_{BW} = iH^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{H.c.} \quad (2-24d)$$

$$O_{WW} = iH^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{H.c.} \quad (2-24e)$$

These operators introduce interactions that involve derivatives of gauge fields and the Higgs field, thus incorporating effects that are quadratic or higher in field derivatives, typically of the contributions at this level.

The theoretical descriptions transition smoothly to practical analysis through the vertex formulation approach. The vertex function for nTGCs, particularly involving the Z boson and a photon, is given by:

$$\Gamma_{Z\gamma V^*}^{\alpha\beta\mu(8)}(q_1, q_2, q_3) = \frac{e(q_3^2 - M_V^2)}{M_Z^2} [(h_3^V + h_5^V \frac{q_3^2}{M_Z^2}) q_{2\nu} \epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2} q_2^\alpha q_{3\nu} q_{2\sigma} \epsilon^{\beta\mu\nu\sigma}] \quad (2-25)$$

where V denotes the gauge bosons involved Z or photon (denoted as γ), q_1 , q_2 , and q_3 are the momenta, h_3^V and h_4^V are the form factors derived from the dimension-8 operators. These form factors encapsulate the modification to the gauge boson interactions introduced by new physics at high-energy scales. The term h_5^V , adjusts the vertex function for gauge bosons, to include a higher order momentum dependency that scales as the cube of the momentum transfer. This inclusion is crucial for capturing subtle effects at high energies that are not addressed by lower-dimensional operators. Essentially, h_5^V ensures that the theoretical framework remains consistent with gauge invariance and Lorentz invariance, even when extending to new physics scenarios beyond the SM.

Form factors h_4^V and h_3^V are linked to the cutoff scales of the corresponding dimension-8

nTGC operators, expressed as:

$$h_4 = -\frac{\text{sign}(\tilde{c}_{G+})}{\Lambda_{G+}^4} \frac{v^2 M_Z^2}{s_w c_w}, \quad h_3^V = 0, \quad \text{for } O_{G+} \quad (2-26a)$$

$$h_3^Z = \frac{\text{sign}(\tilde{c}_{\tilde{B}W})}{\Lambda_{\tilde{B}W}^4} \frac{v^2 M_Z^2}{2s_w c_w}, \quad h_3^\gamma = h_4^V = 0, \quad \text{for } O_{\tilde{B}W} \quad (2-26b)$$

$$h_3^\gamma = -\frac{\text{sign}\tilde{c}_{G-}}{\Lambda_{G-}^4} \frac{v^2 M_Z^2}{2c_w^2}, \quad h_3^Z = h_4^V = 0, \quad \text{for } O_{G-} \quad (2-26c)$$

$$h_4^V = 2h_5^V \quad (2-26d)$$

For clarity within this discussion, we denote

$$h_4 \equiv h_4^Z = \frac{c_w}{s_w} h_4^\gamma \quad (2-27)$$

for simplified expressions.

The relationships highlight how the nTGCs are sensitive to the underlying structure of the gauge sector and potential new physics scales. Understanding these parameters is crucial for predicting potential deviations from the SM observed in high-energy particle collisions, providing a stringent test for the presence of new physics beyond the current theoretical models. The latest formulation^[11-14] of nTGCs in the SMEFT framework applied a fully gauge-invariant approach, strictly adhering to the $SU(2) \times U(1)$ symmetry. This modification significantly enhances the theoretical consistency of the model, ensuring that the accurate transformation between the SMEFT and Effective Vertex approach, maintaining reliability to the fundamental electroweak gauge principles throughout the theoretical formulation.

nTGCs can be probed in current high-energy physics experiments, such as those conducted at the LHC, and are also within the reach of future lepton colliders like the Circular Electron Positron Collider (CEPC)^[36]. The study of nTGCs not only tests theoretical predictions but also enhances the sensitivity and scope of searches for new phenomena. This research holds significant potential to transform our understanding of particle interactions, thereby providing a richer, more comprehensive picture of particle physics. In essence, the exploration of nTGCs in SMEFT underscores an exciting frontier in particle physics, bridging current research capabilities with the quest for deeper theoretical insights and the potential uncovering of new fundamental forces of particles.

Chapter 3 The LHC and ATLAS Detector

The Large Hadron Collider (LHC)^[37], located at the Swiss-French border, is the largest and most powerful particle accelerator in the world. It consists of a 27-kilometer ring of superconducting magnets with a number of accelerating structures to boost particle energy. With the achievement of the first collisions at the end of 2009, the LHC has initiated a new era in particle physics by creating a long period of substantial discoveries and scientific progresses. A Toroidal LHC Apparatus (ATLAS) is one of the key detectors installed at the LHC. As one of two general-purpose detectors, ATLAS probes a extensive range of physics phenomena, from the Higgs boson to new physics beyond the SM.

3.1 Introduction to the Large Hadron Collider

3.1.1 Accelerating System at the LHC

The LHC at the European Organization of Nuclear Research (CERN) is a landmark achievement in particle physics, designed to enhance particle energies through a complex array of accelerators. Protons in the beams are accelerated up to 7 TeV each, enabling collision energy of up to 14 TeV. The LHC has achieved such high energies in its first operational run in between 2011 and 2012, reaching 7 and 8 TeV. And the collision energy was increased to 13 TeV in the subsequent runs from 2015 to 2018, facilitating more profound explanations into the building blocks of the matter and the forces. The acceleration of the beams is a multi-stage process that begins with a series of low-energy accelerators, proceeding to high-energy accelerators for final acceleration. The intricate process is divided into five distinct stages, with each stage playing a crucial role in the particle acceleration for collisions. The schematic illustration of the LHC's accelerator complex array is shown in Fig. 3–1.

- **Linear Accelerator (LINAC4)** The acceleration journey of particles starts with the Linear Accelerator LINAC4^[39], which became the initial source of proton beams for collisions in 2020. Protons are liberated from hydrogen molecules in a strong electric field and subsequently accelerated to approximately 160 MeV. The integration of LINAC4 allows for a more efficient accumulation of particles in the synchrotron with a simplified injection and reduced beam loss.

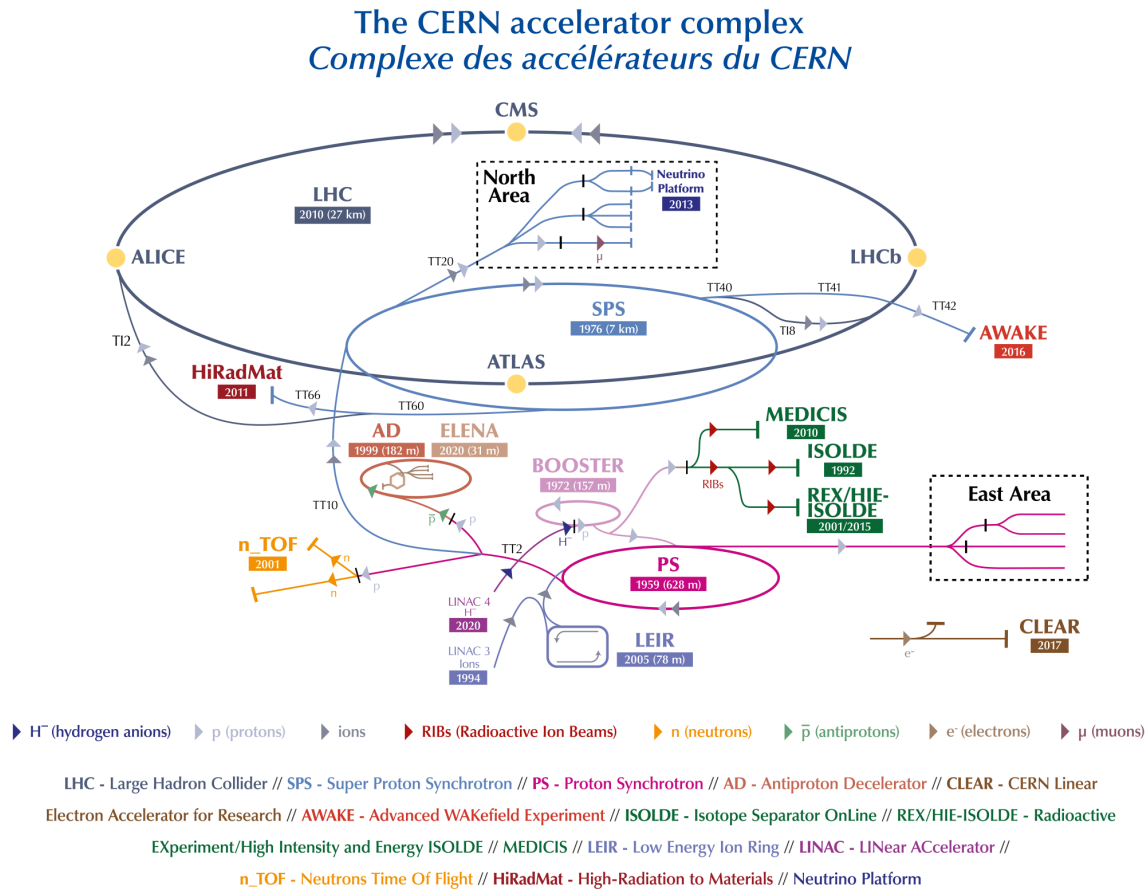


Figure 3–1 Schematic diagram of LHC accelerator system^[38]. An overview of various accelerating components of LHC located at CERN.

- **Proton Synchrotron Booster (PSB)** Following the initial acceleration in LINAC4, protons are moved to the PSB and further accelerated to 2 GeV, setting the stage for subsequent injection into the next phase of acceleration. The PSB^[40] significantly enhances the beam's intensity by 100 times, which is crucial for the efficiency of the third acceleration stage.
- **Proton Synchrotron (PS)** The PS^[41] is a key component in the complex of the particle accelerators. With a circumference of 628 meters, this circular accelerator boosts protons energy up to 26 GeV. Acting as an intermediary component, the PS accepts protons from the PSB and further accelerates protons before being transferred to the next stage.
- **Super Proton Synchrotron (SPS)** The SPS^[42] is the second largest machine in the

entire accelerator complex with nearly 7 kilometers in circumference. Serving as the final preparatory accelerator before the LHC, proton beams from the SPS are accelerated to 450 GeV each at this stage. It is one of the major accelerators at CERN and has played a crucial role in the discovery of W and Z bosons, with the SPS running as a proton-antiproton collider in the 1980s.

- **Large Hadron Collider (LHC)** The LHC^[43] first operated in 2008 as the last addition to CERN's accelerator complex. A circumference of 27 kilometers ring was designed to accelerate particle energies up to 7 TeV. Within this structure, two proton beams travel at velocities nearing the speed of light in opposite directions through separated beam pipes. Strategically, these high-energy collisions take place at four distinct points along its circumference, where four primary experiments are situated correspondingly.

The acceleration network of the LHC is described by a suite of technical parameters that are crucial for understanding the capabilities. A summary of the fundamental beam parameters for these accelerators are listed in Tab. 3–1.

Machine	L [m]	Relative	ρ [m]	Beam Momentum [GeV/c]	Bunches
LINAC	30		-	10^{-4}	4×2
PSB	157		8.3	0.05	4×2
PS	628.318	1	70.676	1.4	72
SPS	6911.56	11×PS	741.257	26	4×72
LHC	26658.883	27/7×SPS	2803.98	450	2×2808

Table 3–1 Length (circumference), bending radius ρ and beam momentum at injection of the main accelerators in the LHC injection chain^[44].

The LHC utilizes Radiofrequency^[45] (RF) cavities for particle acceleration, and superconducting electromagnets employed to ensure the stability, precision and safety of the particle beams. The LHC is equipped with 16 RF cavities with the capability of oscillating at 400 MHz, crucial for enhancing the energy of particles from 450 GeV to 6.5 TeV within around 20 minutes. This system ensures that only protons synchronized with the RF field are accelerated to the desired energy. Protons with different energies or arriving at non-ideal time are corrected through acceleration or deceleration to stay as close as the required energy, being assembled into "Bunches" at LINAC. The superconducting magnet system^[46] in the LHC is a key component, consisting of 1232 dipole magnets along with 392 quadrupole magnets. The

dipole magnets bend the particle beams, while the quadrupole magnets performing the critical task of squeezing the beams to increase the possibility of collisions. The magnetic field is generated by main dipole magnets up to 8.3 Tesla at a current strength of 11080 amperes. Moreover, other magnets also play a crucial role in the particle experiment magnets, subsequent detection and measurement of products after collisions. This elaborate magnet system enables the LHC to function as an efficient particle collider and a sophisticated facility for high-energy physics research.

Within the LHC, four major experimental detectors are constructed at different locations. ATLAS^[47] (A Toroidal LHC Apparatus) and CMS^[48] (Compact Muon Solenoid) function as general-purpose detectors, exploring a wide range of physics, including probing for the Higgs boson, potential extra dimensions, and constituents of dark matter. Despite sharing similar scientific goals, each detector employs distinct methodologies and apparatus configurations. Complementing these, ALICE^[49] (A Large Ion Collider Experiment) and LHCb^[50] (The Large Hadron Collider beauty) further enhance the LHC's research capabilities. ALICE is dedicated to the study of matter at extreme energy densities produced in heavy ion collisions, and to the advanced understanding of quark-gluon plasma, a state of matter thought to have existed immediately after the Big Bang. LHCb specializes in examining the subtle differences between matter and antimatter, particularly through the study of particles containing the "beauty quark" or "bottom quark", thus investigating a new path to the asymmetry of the universe.

3.1.2 Beam Structure and Luminosity

In the LHC, the proton beams are segmented into discrete packets known as "bunches". Each beam consists of approximately 2808 bunches, with each bunch containing around 1.2×10^{11} protons. This configuration facilitates an intense collision rate, yielding roughly one billion particle collisions per second. The ability of the particle accelerator to produce the required number of collisions is quantified by the concept of luminosity^[51]. The instantaneous luminosity ($\mathcal{L}$) of the LHC is defined as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \sigma_x \sigma_y} F \quad (3-1)$$

where:

- N_b : the number of bunches per beam
- n_b : the number of protons per bunch at the Interaction Point (IP)
- f_{rev} : the revolution Frequency, indicating the rate at which a single proton a bunch completes one full orbit of the accelerator ring
- γ_r : the Lorentz factor of accelerated particle
- σ_x, σ_y : the horizontal and vertical beam sizes respectively, typically around $2.5 \mu m$ in the LHC
- F : the geometric reduction factor, accounts for the decrease in the luminosity due to the crossing angle or the beam offset at the IP

The LHC is designed to achieve a maximum instantaneous luminosity of $10^{34} cm^{-2}s^{-1}$, and reached a peak instantaneous luminosity of $2 \times 10^{34} cm^{-2}s^{-1}$ in 2018 which is beyond the expectation for the LHC's performance.

The integrated luminosity, proportional to the total collisions collected within a time interval, is given by the equation:

$$\mathcal{L}_{int} = \int \mathcal{L}(t) dt \quad (3-2)$$

where:

- $\mathcal{L}(t)$: denotes the instantaneous luminosity
- dt : the duration of data collection interval

Expressed in fb^{-1} , where $1 fb^{-1} = 10^{-43} m^{-2}$, the integrated luminosity represents the number of collected events for specific physics processes.

The LHC aims at high-rate collisions to maximize the probability of new discoveries, which leads to multiple simultaneous collisions within the same bunch crossing, known as "pileup"^[52]. Pileup is a significant factor in physics analyses as it affects the objects in various way, from the additional energy deposition to the mis-reconstruction of backgrounds. Pileup is measured by the mean number of interactions per bunch crossing. The distribution of pileup events is shown in Fig. 3-2.

3.1.3 Operation Status

During the Run 2 data-taking of the LHC from 2015 to 2018, there was a significant progress achieved both in the statistics and the quality of data collection. The higher the luminosity, the higher the number of collisions available for study and the greater chance

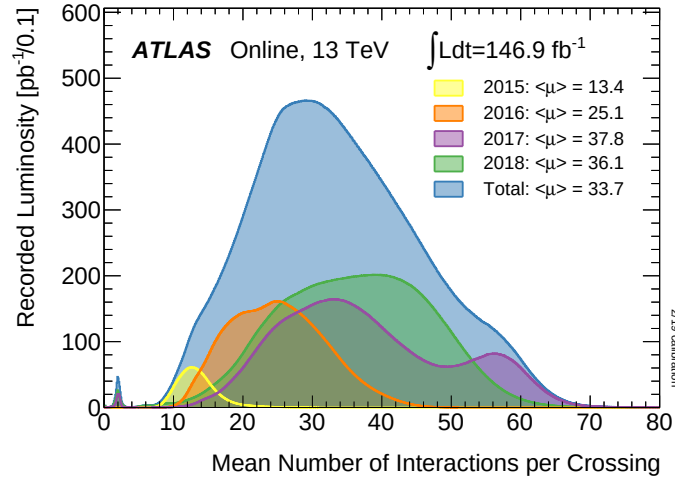


Figure 3–2 Luminosity-weighted distribution^[53] of the mean number of interactions per bunch crossing from 2015 to 2018 proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$, collected by the ATLAS detector.

of observing yet unknown rare processes. Around 150 fb^{-1} of proton-proton collision data were recorded, of which 94% are good for physics analysis. The LHC's achievement in luminosity reflects the continuous improvement over the years.

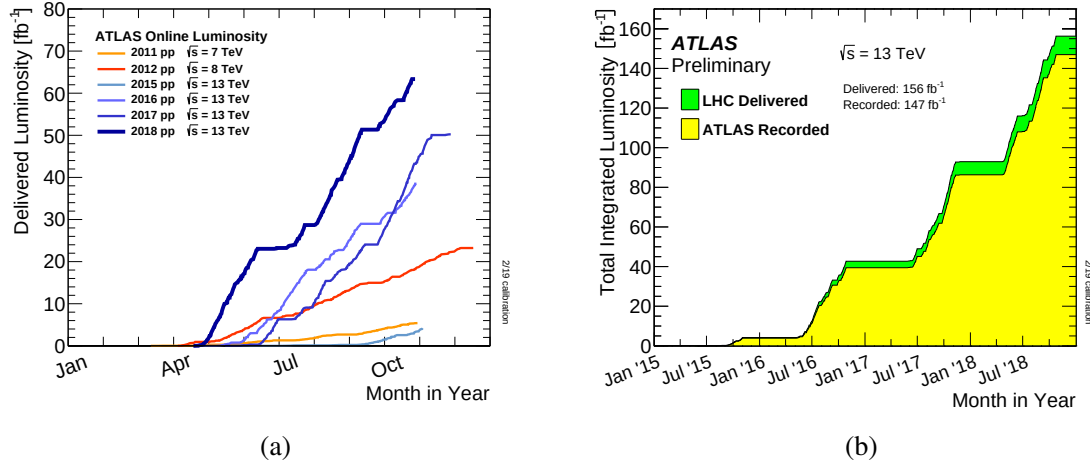


Figure 3–3 Luminosity summary plots over multiple years including full Run2^[54]:
Left: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy proton-proton collisions.
Right: Cumulative luminosity versus time delivered to ATLAS (green) and recorded by ATLAS (yellow) during stable beams for proton-proton collisions at 13 TeV in the LHC Run2.

The graph on the left of Fig. 3–3 illustrates the evolution of delivered luminosity since

2011, culminating in 2018 as collected by ATLAS's data acquisition. The increase in delivered luminosity, emphasizes the increase of the collider in efficiency and power. The right graph of Fig. 3-3 details the cumulative integrated luminosity over time, with 156 fb^{-1} collision data delivered and 147 fb^{-1} recorded by the ATLAS. With the enhancement of the luminosity collected by the ATLAS detector, it is crucial for analyses that may lead to scientific breakthroughs. These advancements allow for more extensive probing of the SM and searches for new physics beyond the SM, such as supersymmetry, extra dimensions, and dark matter. The increased dataset has provided a wealth of opportunities for discoveries but also requires advanced techniques to isolate signals from numerous interactions.

A comprehensive summary of integrated luminosities (post standard data-quality requirements) and associated uncertainties are listed in Tab. 3-2. This table details the integrated luminosities for the LHC from 2015 to 2018, and also provides the calibration uncertainties for each year of data-taking. The categorization listed in this table not only quantifies the extensive collision data collected by ATLAS over these years, but also reflects on the precision of the luminosity measurements.

3.2 Introduction to the ATLAS Experiment

The ATLAS (A Toroidal LHC ApparatuS)^[47] experiment, one of the two general-purpose particle physics projects situated at the LHC, is designed to explore the full discovery potential of the LHC. As the largest detector ever constructed with 46 meters long and 26 meters in diameter, the construction of the ATLAS experiment represents a significant advancement in science. ATLAS facilitates the pursuit of answers to pivotal questions about the fundamental nature of the universe through high-precision measurements.

3.2.1 Overview and Physical Goals

Situated at CERN, the ATLAS experiment demonstrates international collaboration in experimental particle physics. The ATLAS detector is designed as a general-purpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle, providing a comprehensive capture of particle interactions. The construction of ATLAS was driven by the goal to probe new phenomena at the TeV scale, exploring the frontiers of the SM and beyond through detailed examination of a great amount of physics

Data Sample	2015	2016	2017	2018	Comb.
Integrated Luminosity [fb^{-1}]	3.24	33.40	44.63	58.79	140.07
Total Uncertainty [fb^{-1}]	0.04	0.30	0.50	0.64	1.17
Uncertainty Contributions [%]:					
Statistical Uncertainty	0.07	0.02	0.02	0.03	0.01
Fit Model *	0.14	0.08	0.09	0.17	0.12
Background Subtraction *	0.06	0.11	0.19	0.11	0.13
FBCT bunch-by-bunch Fractions *	0.07	0.09	0.07	0.07	0.07
Ghost-charge and Satellite Bunches *	0.04	0.04	0.02	0.09	0.05
DCCT Calibration *	0.20	0.20	0.20	0.20	0.20
Orbit-drift Correction	0.05	0.02	0.02	0.01	0.01
Beam Position Jitter	0.20	0.22	0.20	0.23	0.13
Non-factorisation effects *	0.60	0.30	0.10	0.30	0.24
Beam-beam Effects *	0.27	0.25	0.26	0.26	0.26
Emittance Growth Correction *	0.04	0.02	0.09	0.02	0.04
Length Scale Calibration	0.03	0.06	0.04	0.04	0.03
Inner Detector Length Scale *	0.12	0.12	0.12	0.12	0.12
Magnetic Non-linearity	0.37	0.07	0.34	0.60	0.27
Bunch-by-bunch σ_{vis} Consistency	0.44	0.28	0.19	0.00	0.09
Scan-to-scan Reproducibility	0.09	0.18	0.71	0.30	0.26
Reference Specific Luminosity	0.13	0.29	0.30	0.31	0.18
Subtotal vDM calibration	0.96	0.70	0.99	0.93	0.65
Calibration Transfer *	0.50	0.50	0.50	0.50	0.50
Calibration Anchoring	0.22	0.18	0.14	0.26	0.13
Long-term Stability	0.23	0.12	0.16	0.12	0.08
Total Uncertainty [%]	1.13	0.89	1.13	1.10	0.83

Table 3–2 Summary of the integrated luminosities, after standard data-quality requirements, and uncertainties for the calibration sources of each individual year in Run 2^[55]. Relative uncertainties are displayed in percent. Contributions with an asterisk mark “*” are considered fully correlated between years, while the other uncertainties are considered uncorrelated.

processes.

The ATLAS detector is designed to enhance our understanding of fundamental physics, including the constituents and forces that govern the universe. It also played a pivotal role in the search of the Higgs boson, the detection of which was the benchmark for quantifying the performance of the detector, completing the key point of the SM predictions of particle

physics with the discovery of Higgs boson in 2012. Furthermore, ATLAS is dedicated to perform high precision measurements of the SM, the most comprehensive theory to explain the mechanism of the universe. This commitment not only involves the measurement of known processes with extraordinary precision, but also includes the searches for any potential deviation that could be the sign of new physics beyond the SM. In addition, ATLAS also examines the fundamental forces, particularly the electroweak forces mediated by the W and Z bosons, as well as strong forces responsible for binding quarks within protons and neutrons under various conditions. The investigation into the behaviors and interactions of third-generation quarks, notably the top and bottom quarks, is crucial for understanding matter-antimatter asymmetry in the universe.

Given that the signal processes of interest normally have exceptionally small cross-sections, the LHC is tasked with providing high-luminosity beam and correspondingly high interaction rates. This presents a critical challenge in isolating candidate events for new physics among a vast number of collisions. Consequently, it is imperative for the detector to exhibit robust performance in particle identification. The design principles of the detector have been formulated with these essential objectives^{[56][57]}:

- Achieving wide acceptance in pseudorapidity (η) with near-complete azimuthal angle (ϕ) coverage, facilitating measurements in all transverse directions relative to the beam axis. Pseudorapidity is related to the polar angle (θ) where θ is the angle from the z direction along the beam, and azimuthal angle is measured around the beam axis.
- Providing robust electromagnetic calorimetry essential for electron and photon identification, complemented by a hadronic calorimeter for precise jet and missing transverse energy (E_T^{miss}) measurements.
- Ensuring high-precision muon momentum measurements, capable of delivering accurate rate measurements at peak luminosity with the external muon spectrometer.
- Delivering efficient tracking at high luminosity for precise lepton momentum measurements, electron and photon identification, tau and heavy-flavour quark identification, with comprehensive event reconstruction at low luminosity.
- Wide acceptance and high performance guarantee in triggering and measuring of particles at low p_T thresholds, optimizing the efficiency for the majority of physics processes of interest at the LHC.

The ATLAS detector was meticulously crafted to support a range of complex physics studies. These principles revolve around ensuring precise measurement, wide detection coverage, and sustained operation even under the intense conditions produced by high luminosities. The primary goals are summarized in Tab. 3–3.

Detector Component	Minimum required resolution	η coverage	
		Measurement	Trigger
Inner Detector	$\sigma_{p_T}/p_T 0.05\% p_T \oplus 1\%$	± 2.5	
Electromagnetic Calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic Calorimeter (Jet)			
Barrel and End-caption	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	± 2.7	± 2.4

Table 3–3 The primary detector performance goals of the ATLAS detector^[56].

3.2.1.1 Coordinate System

In the coordinate system of the ATLAS detector, the beam direction defines the z axis, and the $x - y$ plane is oriented perpendicular to it. The positive x axis extends from the interaction point towards the LHC ring center, while the positive y axis points upwards. Within this framework, the azimuthal angle ϕ is given in the transverse $x - y$ plane around the beam axis, while the polar angle θ describes the angle from the beam axis. The pseudorapidity, denoted as $\eta = -\ln \tan(\theta/2)$, is inversely related to the polar angle and is instrumental for calculating particle momenta. Transverse energy $E_T = \sqrt{p_T^2 + m^2}$ measurements and other related variables are defined in the $x - y$ plane, and the distance ΔR in pseudorapidity-azimuthal space is specified for determining spatial separations within the detector, defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The ATLAS detector utilizes a sophisticated tracking system to map the trajectories of charged particles, leveraging a series of helix parameters within a uniform magnetic field shown in Fig. 3–4. Helix parameters used in the ATLAS are categorized into: parameters in the $x - y$ plane and in the $R - z$ plane.

Parameters in the $x - y$ plane:

- $1/p_T$ Reciprocal of the transverse momentum with respect to the beam axis
- ϕ The azimuthal angle, where $\tan \phi \equiv p_x/p_y$

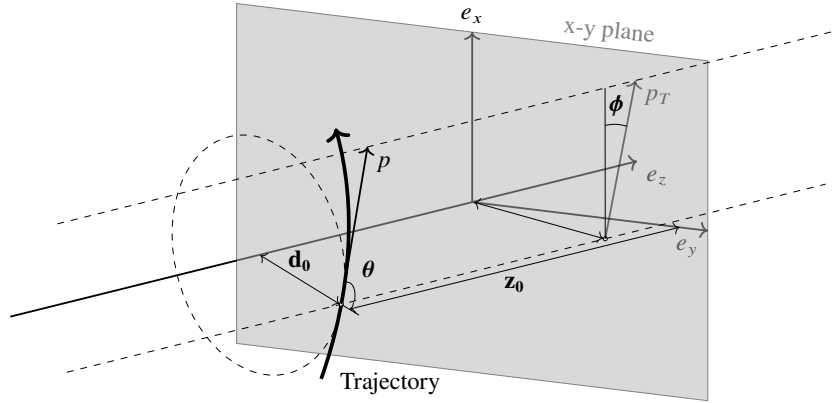


Figure 3-4 Illustration of the global track coordinate of closest approach to the beam axis at the origin of the coordinate system.

- d_0 The transverse impact parameter, defined as the transverse distance, with all variables measured at the point of closest approach to the beam axis at the origin of the coordinate system

Parameters in the $R - z$ plane:

- $\cot \theta$ Cotangent of the polar angle (θ), where $\cot \theta \equiv p_z / p_T$
- z_0 The longitudinal impact parameter, described as the z position of the track at the point of closest approach

Each element of this complex coordinate system plays a vital role in the ATLAS experiment for the ability to detect and analyze particles, thus enhancing the physics capability.

3.2.1.2 Overview of Sub-detector Systems

Each subsystem^[57] within the detector is designed and optimized with distinct characteristics which, when combined, constitute the comprehensive capabilities of the ATLAS detector.

- **Magnet Configuration** The ATLAS detector features a magnet system with a slender superconducting solenoid surrounding the inner detector, and large superconducting toroids arranged with an eight-fold symmetry.
- **the Inner Detector (ID)** Situated within a 7-meters-long, 1.15-meters-radius cylinder, the Inner Detector operates in a 2 tesla solenoidal magnetic field along the beam axis. It is equipped with high-resolution semiconductor pixel and strip detectors for precise tracking, and straw-tube detectors in the outer part for transition radiation detection.

- **Calorimeters** A Liquid-Argon (LAr) electromagnetic (EM) sampling calorimeter is constructed to deliver excellent energy and position resolution within the pseudorapidity range of $|\eta| < 3.2$. The LAr technology extended its utility to hadronic calorimeter in the end-caps, up to $|\eta| < 4.9$. The bulk of hadronic detection is attributed to an innovative scintillator-tile calorimeter, segmented into a large central barrel accompanied by two smaller extended barrel cylinders. The LAr calorimeter is contained in a cylinder with 2.25 m in radius and spanning ± 6.65 m longitudinally along the beam axis. In conjunction, the adjacent scintillator-tile calorimeter covers an outer radius of 4.25 m with a half-length of 6.10 m. The total weight of the calorimeter system is around 4000 Tonnes.
- **Muon Spectrometer** The muon spectrometer, surrounding the calorimeter, features an air-core toroid magnet system yielding a large magnetic field. Exceptional muon momentum resolution is achieved through three stations of high-precision tracking chambers, ensuring minimal effects of multiple scattering and optimal resolution of muon momentum. These are supplemented by rapid-response trigger chambers for effective muon trajectory detection.
- **Overall Dimensions** The overall size of the ATLAS detector is defined by the muon spectrometer. The boundaries, marked by a 11-meter radius, coupled with a half-length of 12.5 meters for barrel toroid coils. The forward muon chambers are situated nearly 23 meters from the interaction point. Altogether, the total weight of the ATLAS detector is about 7000 metric tonnes.

The ATLAS detector is designed and constructed within such a comprehensive framework composed of various complex subsystems and components, as shown in Fig. 3–5. The experiment is operated to run at high luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, ensuring the collection of abundant data. The detector's versatility in capturing a wide range of event signatures is vital for reliable and comprehensive physics analyses within the intensive collision environment of the LHC. In the following sections, a comprehensive overview of each subsystem of the ATLAS experiment will be provided, delving into the intricacies of the design, the function of each component, and the highlight of how they collectively contribute to the overarching scientific objectives of the experiment.

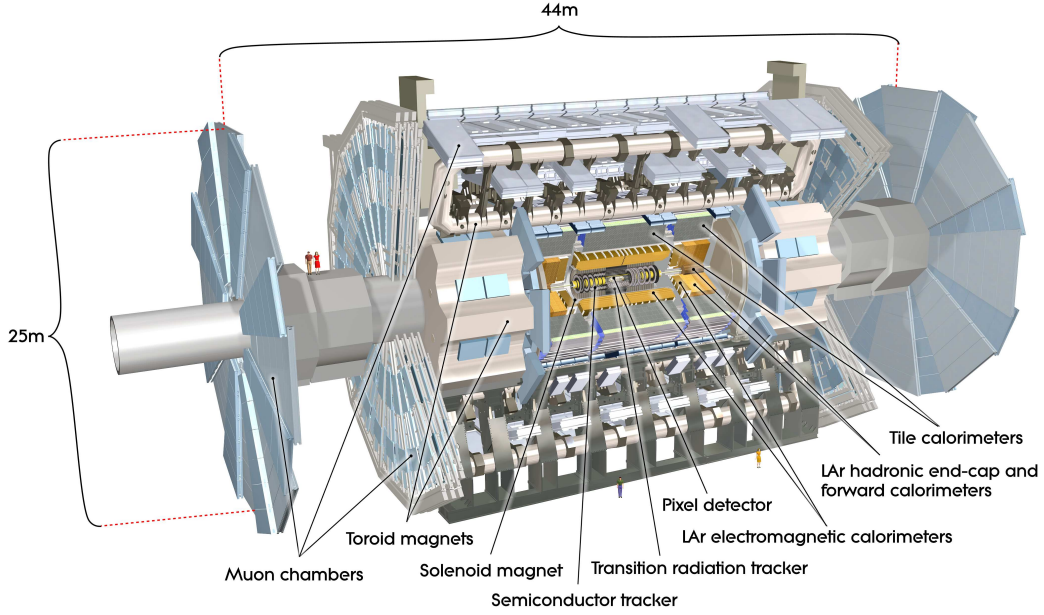


Figure 3–5 Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes.

3.2.2 Detector Components and Subsystems

The ATLAS detector, an integral component of the LHC, is constituted by a series of subsystems. These are pivotal in acquiring intricate details regarding particle interactions produced in high-energy proton-proton collisions. Collectively, the subsystems synthesize a comprehensive display of the particle interactions, thereby facilitating the physical investigation into the fundamental constituents of the universe. The following sections describe a structured overview of the ATLAS detector from the innermost elements to the outer layers.

3.2.2.1 Inner Detector

The Inner Detector (ID)^[58] of the ATLAS experiment is designed to precisely reconstruct the tracks and interaction vertices with high efficiency, playing a crucial role in conjunction with the calorimeter and muon spectrometer for the identification of electrons, muons, and photons. It also furnishes additional information important for measuring the decay vertices of short-lived particles. At the interaction point, an average of approximately 1000 particles emerges every 25 ns within the pseudorapidity range of $|\eta| < 2.5$, presenting a dense landscape of tracks. To achieve the demands of high momentum and vertex resolution, which is essential for the measurement of tracks, the ID is configured with a composite architecture

to enable measurements with high precision. The integration of the Semiconductor Tracking (SCT) detector with the Transition Radiation Tracker (TRT), which is composed of straw tubes, results in a detector of fine granularity. This sophisticated structure design ensures robust pattern recognition capabilities and affords high-precision measurements in both azimuthal (ϕ) and longitudinal (z) coordinates.

Mechanically, the ID consists of three units:

- **The Pixel Detector** An instrument with high-granularity, crafted to capture measurements positioned as close as possible to the IP. It provides high-resolution in the measurement over the entire coverage and impact parameter resolution, as well as the determination for trajectories and interaction points of short-lived particles, notably b-quarks and tau leptons. The detector consists of an array of 140 million pixel elements, each with sizes of $50\ \mu\text{m}$ in $R - \phi$ direction and $3000\ \mu\text{m}$ in the z axis, providing an unambiguous two-dimensional space point segmentation. The pixel system, consisting of three barrel layers at average radii of 4, 11 and $14\ \text{cm}$, is complemented by four disk layers extending from 11 to $20\ \text{cm}$., ensuring a wide angular coverage. This modular setup includes around 1500 barrel and 1000 disk modules. Each barrel unit, with size of $62.4\ \text{mm}$ by $22.4\ \text{mm}$, is equipped with 61440 pixel elements and served by 16 chips in an array of 24×160 . The design of such system ensures that the contribution of each layer to the overall radiation length is exceptionally low, remaining below 1.39 % in simulations, thus minimizing the impact on the detector's performance.
- **The Semiconductor Tracker (SCT)** The SCT system within the ATLAS detector is engineered to provide four precision measurements for each track in the intermediate radial range, enhancing the capability of the detector to measure particle momentum, determine impact parameters, and locate vertex position with high accuracy. The high-granularity also allows to provide good pattern recognition. With an extensive area of $61\ \text{m}^2$ and 6.2 million readout channels employed, the silicon microstrip detector in the SCT system in the barrel layers enable resolutions of $16\ \mu\text{m}$ in the $R - \phi$ plane and $580\ \mu\text{m}$ along the z axis. The individual sensors, featuring 768 readout strips with an $80\ \mu\text{m}$ pitch, are crucial for distinguishing particle tracks separated by more than approximately $200\ \mu\text{m}$. The forward modules are constructed to cater to the needs of the high-radiation environment, functioning within the specified pseudorapidity range

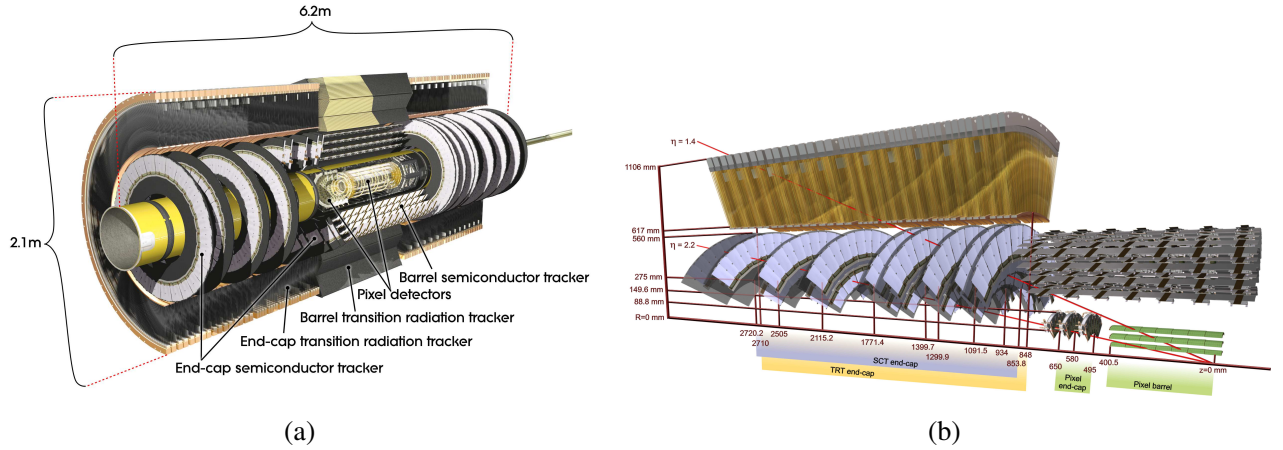
of $|\eta| \leq 2.5$. This structure incorporates advanced design features for cooling and thermal stability, utilizing materials with low coefficients of thermal expansion and employing an innovative cooling method. The meticulous design of such system is tailored to operate efficiently in the LHC for a projected duration from 2008 to 2025.

- **The Transition Radiation Tracker (TRT)** The TRT in the ATLAS detector is essential for identifying electrons among many charged particles. Transition radiation, which the TRT detects, is a form of X-ray emitted when charged particles traverse the boundary between materials with different properties. Composed of an array of gas-filled tubes, the TRT records particle trajectories and harnesses transition radiation to identify electrons. The TRT of the ATLAS detector features modules with 329 to 793 straws each, covering a radial range from 56 to 107 *cm*. The end-cap regions consist of 18 wheels, with hit rates ranging from 6 to 18 MHz. The TRT maintains a position accuracy of approximately 170 μm , with an overall measurement accuracy better than 50 μm despite high counting rates. This precision is achieved through advanced electronics, including low-noise preamplifiers and radiation-hard processes, ensuring the TRT performs effectively within the LHC's high-luminosity conditions. The TRT enhances the ATLAS Inner Detector's capabilities by providing additional hits for precise momentum measurements and improving pattern recognition, pivotal for tracking particles and distinguishing between electrons and hadrons.

The overall and a schematic view of the Inner Detector is presented in Fig. 3–6, which illustrates the structure from the innermost to the outermost elements. Tab. 3–4 lists the design specifications and the resolution of space-point measurements of the Inner Detector.

3.2.2.2 Calorimeters

The calorimeter system^[60] within the ATLAS detector, is an array of sampling devices which are engineered for extensive pseudorapidity coverage up to $|\eta| < 4.9$. The design specifications and segmentations are summarized in Tab. 3–5 and a overview of the calorimeter is visualized in Fig. 3–7. Within the calorimeter suite, the electromagnetic (EM) calorimeter, with its fine granularity, is tuned for the precise measurement of electrons and photons, aligning with the regions spanned by the inner detector. The rest of the calorimeter system, while employing coarser granularity, is nonetheless designed to fulfill the rigorous physics requirements for the reconstruction of jets and the measurement of missing transverse energy

Figure 3-6 Cut-away view of the Inner Detector^[59].

Left: a overall cutaway view of the layout of the Inner Detector. Right: a schematic view of the Inner Detector, including the barrel layers and the endcap disks of Pixel Detector and SCT, and the TRT endcap straw layers.

System	Position	Area (m^2)	Resolution $\sigma(\mu m)$	Channels (10^6)	η coverage
Pixels	1 removable barrel layer	0.2	$R\phi = 12, z = 66$	16	± 2.5
	2 barrel layers	1.4	$R\phi = 12, z = 66$	81	± 1.7
	4 end-cap disks on each side	0.7	$R\phi = 12, R = 77$	43	1.7 - 2.5
Silicon strips	4 barrel layers	34.4	$R\phi = 16, z = 580$	3.2	± 1.4
	9 end-cap wheels on each side	26.7	$R\phi = 16, R = 580$	3.0	1.4 - 2.5
TRT	Axial barrel straws		170 (per straw)	0.1	± 0.7
	Radial end-cap straws 36 straws per tracks		170 (per straw)	0.32	0.7 - 2.5

Table 3-4 Basic design parameters and resolutions of the Inner Detector^[58]. The resolutions listed are typical values(the actual resolution in each detector varies with $|\eta|$).

E_T^{miss} .

The ATLAS calorimeters are designed for containment of both electromagnetic and hadronic showers, minimizing the possibility of particles reaching the muon system, known as punch-through. The electromagnetic calorimeter depth exceeds 22 radiation lengths (X_0) in the barrel and surpasses 24 X_0 in the end-caps, ensuring significant absorption of high-energy photons and electrons. The interaction depth (λ) is 9.7 in the barrel and 10 λ in the end-

caps, providing the containment necessary for jet reconstruction and assessment of missing transverse energy (E_T^{miss}). The total calorimeter thickness, including the support structure, measures 11λ at pseudorapidity $\eta = 0$, demonstrated by measurement and simulation to mitigate muon punch-through below critical thresholds. This comprehensive coverage is vital for precise E_T^{miss} measurements, a key aspect in searches for new physics beyond the Standard Model.

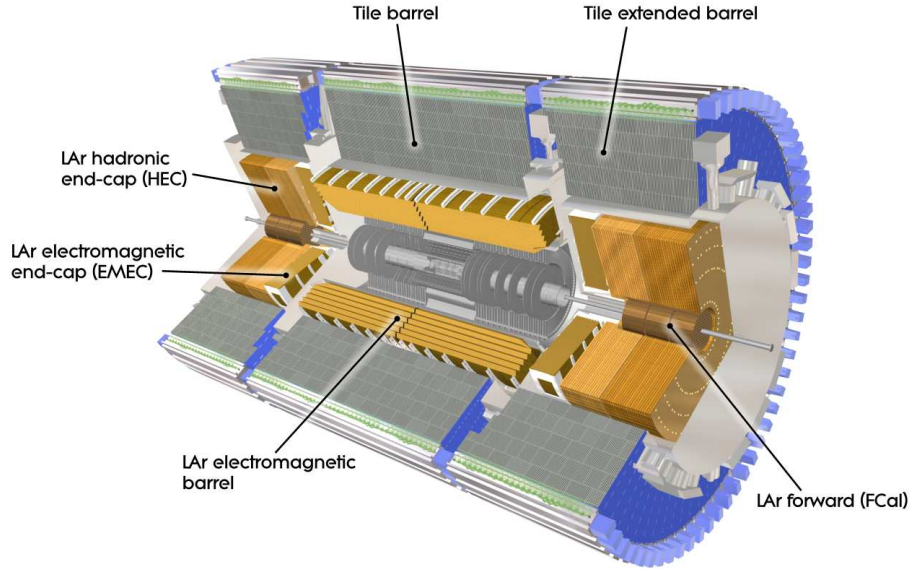


Figure 3-7 Cut-away view of the ATLAS calorimeter system.

Liquid Argon (LAr) electromagnetic calorimeter The EM calorimeter, meticulously segmented into a barrel part ($|\eta| < 1.475$) and two end-cap components ($1.375 < |\eta| < 3.2$), is instrumental in precise determination of electron and photon energies across a broad pseudorapidity range. Optimized material distribution in conjunction with the central solenoid enhances its functionality, enabling fine granularity where needed for precise measurements. The unique accordion geometry ensures consistent detection efficiency and coverage, a crucial feature for the accurate reconstruction of events and insightful analysis in high-energy physics experiments. The subsequent discussion will explore the composition and parameters of EM^[61] from several aspects:

- **Barrel calorimeter** The barrel calorimeter of the ATLAS detector is encased within a 6.8 meters long cryostat with an outer radius of 2.25 meters. This structure is built from

		barrel	End-cap
EM calorimeter			
Number of layers and $ \eta $ coverage			
Presampler	1	$ \eta < 1.52$	$1.5 < \eta < 1.8$
Calorimeter	3	$ \eta < 1.35$	$1.375 < \eta < 1.5$
	2	$1.35 < \eta < 1.475$	$1.5 < \eta < 2.5$ $2.5 < \eta < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $ \eta $			
Presampler	0.025×0.1	$ \eta < 1.52$	$1.5 < \eta < 1.8$
Calorimeter 1st layer	$0.025/8 \times 0.1$	$ \eta < 1.40$	$1.375 < \eta < 1.425$
	0.025×0.025	$1.40 < \eta < 1.475$	$1.425 < \eta < 1.5$
			$1.5 < \eta < 1.8$
			$1.8 < \eta < 2.0$
			$2.0 < \eta < 2.4$
			$2.4 < \eta < 2.5$ $2.5 < \eta < 3.2$
Calorimeter 2nd layer	0.025×0.025	$ \eta < 1.40$	$1.375 < \eta < 1.425$
	0.075×0.025	$1.40 < \eta < 1.475$	$1.425 < \eta < 2.5$ $2.5 < \eta < 3.2$
Calorimeter 3rd layer	0.050×0.025	$ \eta < 1.35$	$1.5 < \eta < 2.5$
Number of readout channel			
Presampler	7808		1536 (both sides)
Calorimeter	101760		62208 (both sides)
LAr hadronic end-cap			
$ \eta $ coverage			$1.5 < \eta < 3.2$
Number of layers			4
Granularity $\Delta\eta \times \Delta\phi$			0.1×0.1
			0.2×0.2 $1.5 < \eta < 2.5$ $2.5 < \eta < 3.2$
Readout channels			5632 (both sides)
LAr forward calorimeter			
$ \eta $ coverage			$3.1 < \eta < 4.9$
Number of layers			3
Granularity $\Delta x \times \Delta y$ (cm)		FCall: 3.0×2.6	$3.15 < \eta < 4.30$
		FCall: $\sim$ four times finer	$3.10 < \eta < 3.15$
		FCall2: 3.3×4.2	$4.30 < \eta < 4.83$
		FCall2: $\sim$ four times finer	$3.24 < \eta < 4.50$
		FCall3: 5.4×4.7	$3.20 < \eta < 3.24$
		FCall3: $\sim$ four times finer	$4.50 < \eta < 4.81$ $3.32 < \eta < 4.60$ $3.29 < \eta < 3.32$ $4.60 < \eta < 4.75$
Readout channels			3524 (both sides)
Scintillator tile calorimeter			
	Barrel	Extended barrel	
$ \eta $ coverage	$ \eta < 1.0$	$0.8 < \eta < 1.7$	
Number of layers	3	3	
Granularity $\Delta\eta \times \Delta\phi$ Last layer	0.1×0.1	0.1×0.1	
	0.2×0.1	0.2×0.1	
Readout channels	5760	4092 (both sides)	

Table 3–5 Main parameters of the calorimeter system^[60].

an aluminum alloy shell that enhances the robustness and provides vacuum insulation. It optimizes the detector performance by reducing material interference with particles. The primary role of shell structure is to support the internal components and maintain the necessary environmental conditions, such as temperature stability and vacuum integrity, which are essential for the accurate operation of the sensitive electronics and superconducting solenoids.

- **End-cap calorimeter** The end-cap calorimeters of the ATLAS detector comprise an electroweak wheel and two hadronic wheels, tailored to cover pseudorapidity ranges up to $|\eta| < 3.2$. The accordion-shaped geometry of the EM calorimeter scales with the radius to provide efficient plate distribution and ensure comprehensive pseudorapidity coverage. Each end-cap EM wheel consists of two concentric wheels that extend pseudorapidity coverage: the larger spans from 1.4 to 2.5, and the smaller from 2.5 to 3.2. Constructed from aluminum with vacuum insulation to maintain thermal stability, these calorimeters house 768 plates in the larger wheel and 256 in the smaller, all within an outer radius of 2.25 meters, thus enabling precise formation of readout cells vital for energy measurement. The accordion-shaped geometry of the EM calorimeter enhances the pseudorapidity coverage by efficiently distributing absorber plates and integrating readout electronics.
- **Presampler** The presampler of the ATLAS detector functions to correct the energy loss from the electrons and photons before entering the calorimeter, and to ensure accurate energy measurements. In transition zones between the barrel and end-cap at around $|\eta| < 1.4$, a scintillator layer is used to recover the energy measurement particularly for jet, electron, and photon. The end-cap wheels are placed as close to the barrel modules as possible, with the presampler integrated to minimize EM calorimetry gaps.
- **Lead thickness and signal height** The ATLAS EM calorimeter requires a minimum of 24 radiation lengths (X_0) in the barrel and 26 X_0 in the end-caps. Lead thicknesses between 1.1 and 2.2 mm are employed to fine-tune the sampling fraction and ensures a uniform signal response, which is vital for accurate particle energy reconstruction. This dedicated design ensures a stable and precise calorimetric performance, vital for fast response times in triggering applications, where a high voltage across varying radii

guarantees minimal signal variation for a flat response from the detector.

- **Granularity of the samples** The design of ATLAS calorimeter is refined to achieve precise measurements up to $|\eta| < 2.5$, with an optimized granularity of 0.025 in both pseudorapidity and azimuth for the central tower, essential for effective particle identification. It features a first sampling layer with a depth of $6 X_0$ and a primary layer with $24 X_0$ lengths, coupled with a presampler granularity of 0.025×0.1 . The configuration enables precise energy reconstruction, calibrated to meet the intricate needs of particle physics investigation.

Hadronic calorimeters The ATLAS hadronic calorimeter (HCAL)^[60], covers a pseudorapidity range up to $|\eta| < 5$, integrated a suite of sophisticated techniques for various demands of the radiation environment and operation requirements. The Tile calorimeter, compromising both the barrel and extended barrel components up to $|\eta| < 1.6$, uses an iron-scintillating tile sandwich, while the Liquid Argon (LAr) calorimeter system is implemented in the region of approximately $1.5 < |\eta| < 4.9$. With a comprehensive calorimeter thickness of 11 interaction length (λ) at $\eta = 0$, the system provides effective containment of hadronic showers and reducing punch-through for muon spectrometer.

- **Tile calorimeter** The Tile calorimeter, positioned directly outside the EM envelope, covers a pseudorapidity range up to $|\eta| < 1.7$, with its barrel and extended barrel sections covering $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$ respectively. As an important sampling calorimeter, it utilizes steel as absorber and scintillating tiles as the active detection material. The barrel and extended barrels are segmented azimuthally into 64 modules extend radially from an inner radius of 2.28 m to an outer radius of 4.25 m. Divided in depth, the three layers of calorimeter have interaction lengths of 1.5, 4.1 and 1.8 λ for the barrel, plus 1.5, 2.6 and 3.3 λ for the extended barrel, providing a total detector thickness at the outer edge of 9.7 λ at $\eta = 0$. Both sides of scintillating tiles are read out by wavelength-shifting fibers leading to photomultiplier tubes, with the readout cells pseudoprojective towards the interaction point for effective energy measurements.
- **LAr hadronic end-cap calorimeter** The hadronic end-cap calorimeter (HEC) of the ATLAS detector features two independent wheel assemblies behind the end-cap EM calorimeter, integrating with the same LAr cryostats. To ensure seamless energy measurement transitions between the end-cap and forward calorimeter, the HEC covers

the pseudorapidity range extended to $|\eta| < 3.2$, with a slight overlap up to $|\eta| = 1.5$ with the Tile calorimeter. Constructed with 32 identical wedge-shaped modules per wheel, the HEC wheels are sectioned into two depth segments, culminating in four layered structure per end-cap to facilitate detailed particle detection and energy measurements. Closest to the IP, the front wheel layers consist of copper plates with a thickness of 25 mm, transitioning to 50 mm in subsequent layers intercalated with 8.5 mm gaps of liquid argon, thus forming the active sampling region. This configuration is meticulously designed to optimize the calorimeter's performance in detecting high-energy hadronic showers while minimizing muon system penetration.

- **LAr forward calorimeter** The forward calorimeter (FCal), is housed within the end-cap cryostats to improve coverage and reduce background radiation in the muon spectrometer. Recessing its front face by 1.2 m from that of the EM calorimeter mitigates neutron backscatter into the central detector region. This compact design necessitates a high-density calorimeter, which in the ATLAS FCal, achieves about ten interaction lengths. It features three modules in each end-cap: the initial copper module for electromagnetic interactions and subsequent tungsten modules for hadronic events. The metal matrices of modules are punctuated by channels housing an electrode system of rods and tubes, filled with liquid argon. This arrangement, with narrow 0.25 mm gaps in the first module, ensures fine control and accurate energy measurements while avoiding ion buildup.

3.2.2.3 Muon Spectrometer

The ATLAS Muon Spectrometer^[62] is a high-resolution instrument vital for measuring high-momentum muon signatures at the LHC. Its sophisticated design, incorporating air-core toroid magnets, achieves precise muon tracking and stand-alone triggering across varying transverse momentum, pseudorapidity, and azimuthal angles. Within $|\eta| < 1.4$, the barrel toroid magnetically bends muon paths, with end-cap magnets covering the range up to $|\eta| < 2.7$, and a blend of both systems operating in the $1.4 < |\eta| < 1.6$ transition region. A overview of the muon spectrometer is highlighted in Fig. 3–8 and main parameters are summarized in Tab. 3–6. The magnet system in the ATLAS Muon Spectrometer provides a field orthogonal to the muon trajectories, while optimizing resolution by mitigating the effect of multi-scattering. This configuration, specifically designed for high particle fluxes, plays

a pivotal role in shaping the key performance of the spectrometer and ensures the reliability and precision of measurements over the operational longevity.

The ATLAS Muon Spectrometer employs three cylindrical layers of chambers for trajectory tracking along the beam axis in the barrel section, and another three layers in the perpendicular arrangement to cover transition and end-cap regions, ensuring a full-range track measurement capability.

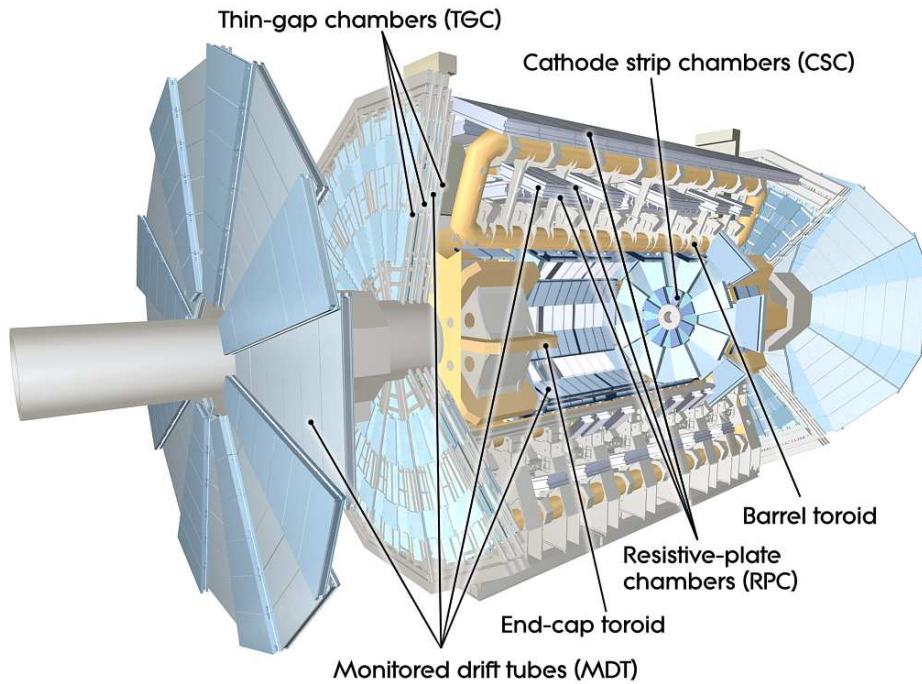


Figure 3–8 Cut-away view of the ATLAS muon system.

The ATLAS muon spectrometer is engineered to accurately track high-momentum muons, a crucial component for experiments at the LHC. Its architecture centers around a set of superconducting air-core toroids, composed of a main barrel and two end-cap magnets, each built with eight coils to provide effective muon trajectory bending over a wide range of pseudorapidities. The barrel toroid operates up to $|\eta| < 1.4$, with the end-cap magnets accommodating $1.6 < |\eta| < 2.7$, ensuring seamless magnetic coverage. This configuration helps maintain resolution despite the potential for scattering and the intense particle flux encountered during LHC operations. The design minimizes the loss of resolution due to scattering, vital for precise muon tracking. Meticulously assembled chambers, incorporating Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), provide high-granularity measurements and em-

Monitered drift tubes - Coverage - Chamber resolution (RMS) in z/R - Chamber resolution (RMS) in ϕ - Chamber resolution (RMS) in time - Number of chambers - Number of channels - Function	MDT $ \eta < 2.7$ (innermost layer: $ \eta < 2.0$) $35 \mu m$ (z) - - 1088 (1150) 339 000 (354 000) Precision tracking
Cathode strip chambers - Chamber resolution (RMS) in z/R - Chamber resolution (RMS) in ϕ - Chamber resolution (RMS) in time - Coverage - Number of chambers - Number of channels - Function	CSC $40 \mu m$ (R) $5 mm$ $7 ns$ $2.0 < \eta < 2.7$ 32 31 000 Precision tracking
Resistive plate chambers - Coverage - Chamber resolution (RMS) in z/R - Chamber resolution (RMS) in ϕ - Chamber resolution (RMS) in time - Number of chambers - Number of channels - Function	RPC $ \eta < 1.05$ $10 \mu m$ (z) $10 mm$ $1.5 ns$ 544 (606) 359 000 (373 000) Triggering, second coordinate
Thin gap chambers - Coverage - Chamber resolution (RMS) in z/R - Chamber resolution (RMS) in ϕ - Chamber resolution (RMS) in time - Number of chambers - Number of channels - Function	TGC $1.05 < \eta < 2.7$ (2.4 for triggering) $2 - 6 \mu m$ (R) $3 - 7 mm$ $4 ns$ 3588 318 000 Triggering, second coordinate

Table 3–6 Main parameters of the Muon Spectrometer^[60]. Numbers in brackets for the MDT's and the RPC's refer to the final configuration of the detector in 2009.

ploy a sophisticated alignment system integral to the spectrometer. The bending power of the spectrometer's magnetic system is high, offering a range of 1.5 to 5.5 Tm in the barrel

and 1 to 7.5 Tm in the end-caps, designed to work effectively across all regions, including where the magnets overlap. Complementing the magnetic setup, the spectrometer's trigger system, featuring Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC), provides sharp triggering and precise coordinate measurement, integral for identifying muon paths orthogonally to the tracking chambers.

In essence, the ATLAS muon spectrometer exemplifies advanced design in high-energy physics instrumentation, blending robust magnetic fields with fine-tuned detection capabilities. It stands as a critical tool for deciphering complex particle interactions at the LHC.

3.2.2.4 Magnet System

The ATLAS magnet system^[60], an integral component which comprises four large superconducting magnets. Encompassing a diameter of 22 meters and extending 26 meters in length, this system can store 1.6 GJ of magnetic field energy and creates a magnetic field exceeding 50 T in a volume of roughly 12000 m³. The positioning and arrangement of the comprehensive overview for magnet system is depicted in the left panel of Fig. 3–9 and its main parameters are listed in Tab. 3–7, while the geometry of magnet windings is systematically displayed in the right panel.

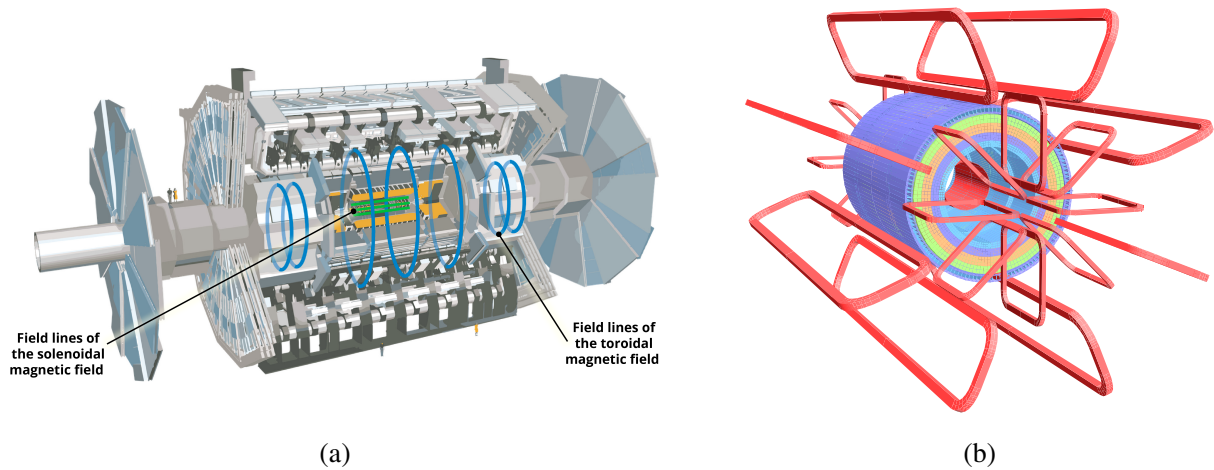


Figure 3–9 Cut-away view of the ATLAS magnet system.

Left: an overview of the ATLAS magnet system. Right: Geometry of magnet windings and tile calorimeter steel. Eight coils in the barrel toroid align together with the end-cap coils for magnetic field generation, encircled by the solenoid winding. The tile calorimeter is illustrated in four distinct magnetic layers, topped with a return yoke. The forward shielding disk is removed for simpler visualization.

Property	Feature	unit	Solenoid	Barrel toroid	End-cap toroids
Size	Inner diameter	m	2.46	9.4	1.65
	Outer diameter	m	2.56	20.1	10.7
	Axial length	m	5.8	25.3	5.0
	Number of coils		1	8	2×8
Mass	Conductor	t	3.8	118	2×20.5
	Cold mass	t	5.4	370	2×140
	Total assembly	t	5.7	830	2×239
Coils	Turns per coil		1154	120	116
	Nominal current	kA	7.73	20.5	20.5
	Magnet stored energy	GJ	0.04	1.08	2×0.25
	Peak field in the windings	T	2.6	3.9	4.1
	Field range in the bore	T	0.9 - 2.0	0.2 - 2.5	0.2 - 3.5
	Overall size	mm ²	30×4.25	57×12	41×12
	Ratio Al:Cu:NbTi		15.6:0.9:1	28:1.3:1	19:1.3:1
	Number of strands (NbTi)		12	38 - 40	40
	Strand diameter (NbTi)	mm	1.22	1.3	1.3
	Critical current (at 5 T and 4.2 K)	kA	20.4	58	60
Conductor	Operating/critical-current ratio at 4.5 K	%	20	30	30
	Residual resistivity ratio (RRR) for Al	> 500	> 800	> 800	
	Temperature margin	K	2.7	1.9	1.9
	Number of units $\times$ length	m	4×2290	$8 \times 4 \times 1730$	$2 \times 8 \times 2 \times 800$
	Total length (produced)	km	10	56	2×13
Heat load	At 4.5 K	W	130	990	330
	At 60 - 80 K	kW	0.5	7.4	1.7
	Liquid helium mass flow	g/s	7	410	280

Table 3-7 Main parameters of the ATLAS magnet system^[60].

The ATLAS magnet system features four components of superconducting magnets^[63]:

- **Central solenoid** The central solenoid, positioned along the beam trajectory, is engineered to provide a 2 Tesla axial magnetic field for the inner detector.
- **Barrel toroid together with two end-cap toroids** The barrel toroid, featuring eight superconducting coils contained in stainless steel, is engineered to generate a magnetic field critical for the operation of the muon spectrometer. This field varies from around 0.5 Tesla in the central region to about 1 Tesla towards the end-cap region. It provides high bending power across the detector, ensuring precise momentum measurements.

3.2.2.5 Trigger and Data-acquisition System

Data management in the ATLAS experiment is designed by an integrated Trigger and Data Acquisition (TDAQ) system^[64-65], enhanced by a Detector Control System (DCS). This is partitioned into distinct subsystems that align with the associated subdetectors, each employing with consistent timing- and trigger-control logic as building blocks. The trigger is segmented into three distinct levels: L1, L2 and the Event Filter which each refines the selection parameters at the previous level and additional criteria.

The trigger system contains different stages and shown in Fig. 3–10:

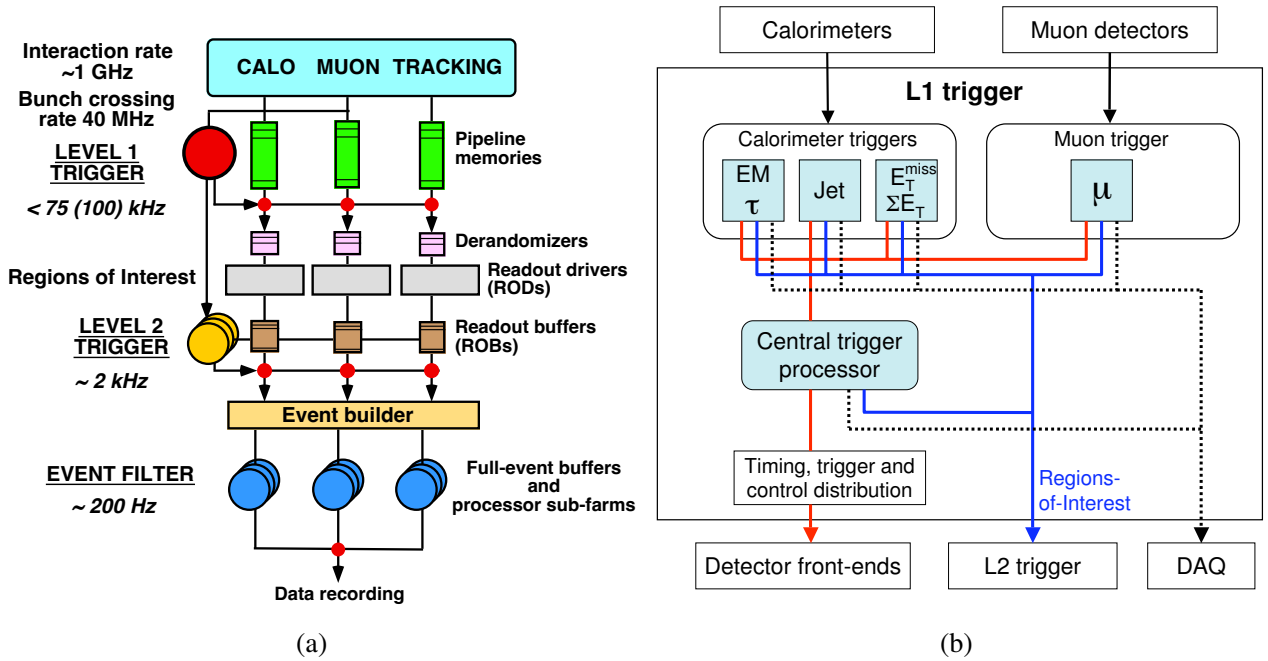


Figure 3–10 Overview of ATLAS trigger system^[66].

Left: A schematic overview of ATLAS trigger system under different levels. Right: Block diagram of the Level 1 triggers.

- **Level-1 (L1) Trigger** The Level-1 Trigger of the ATLAS experiment is executing the initial and most rapid selection of potential physics events. Engineered with customized electronics, it analyzes low-resolution data from selected detector components, the Resistive Plate Chambers (RPC) and Thin-Gap Chambers (TGC). These components are pivotal in detecting high-momentum muons, with the system extending its capabilities to encompass the calorimeter subsystem for the identification of electromagnetic patterns, jets, τ -leptons, missing transverse energy E_T^{miss} , as well as

large transverse energy signatures. Functioning within a 2.5 microseconds window post bunch-crossing, the L1 Trigger refines the event rate to approximately 75 kHz, with a potential to increase to 100kHz. This rapid selection progress is instrumental in isolating high-quality physics events from the vast dataset generated by the LHC, thereby facilitating an effective data processing pipeline.

- **High-Level Trigger - HLT** The High-Level Trigger of the ATLAS detector, which not incorporates the functions of the Level-2 Trigger and the Event Filter, is a sophisticated layer that utilizes advanced computational and networking resources to manage data from detector readouts. The HLT employs Regions-of-Interest (RoIs) identified by the L1 trigger to selectively process data and to optimize event selection by reducing data volume and refining the detection of significant physics events. This integrated system ensures event rates are managed down to a feasible 3.5 kHz, with an average processing time of approximately 40 ms. Moreover, the HLT enhances particle identification, especially distinguishing between electrons and photons, by tuning algorithms for optimal event selection based on detailed data analysis from various detector components, including the calorimeter and muon chamber. The enhanced HLT setup significantly improves threshold parameter definitions and track reconstruction, facilitating a more precise and rapid response in real-time particle detection and reducing the overall event rate to about 200 Hz for detailed offline analysis.

The Data Acquisition System (DAQ)^[60,67-68] of the ATLAS experiment is an integral component, functioning within the trigger system, as illustrated in Fig. 3–11. It is responsible for the handling of event data at the initial L1 trigger rate, involving the collection, temporary storage, and subsequent dispatch as dictated by the L2 trigger, focusing on specified Regions-of-Interest (RoI's). Events are compiled and then shuttled by the DAQ to the event filter once it fulfills L2 selection criteria, ensures the preservation in permanent storage system and evidences the role beyond mere data transition in the ATLAS experiment. Moreover, the DAQ's scope has been extended to active engagement in the configuration, control, and supervisory aspects of the ATLAS detector operators, interfacing seamlessly with the Detector Control System (CDS) for oversight of detector elements. This harmonized operation between the DAQ and the trigger layers introduced a sophisticated data management system, pivotal in discerning and securing related experimental data.

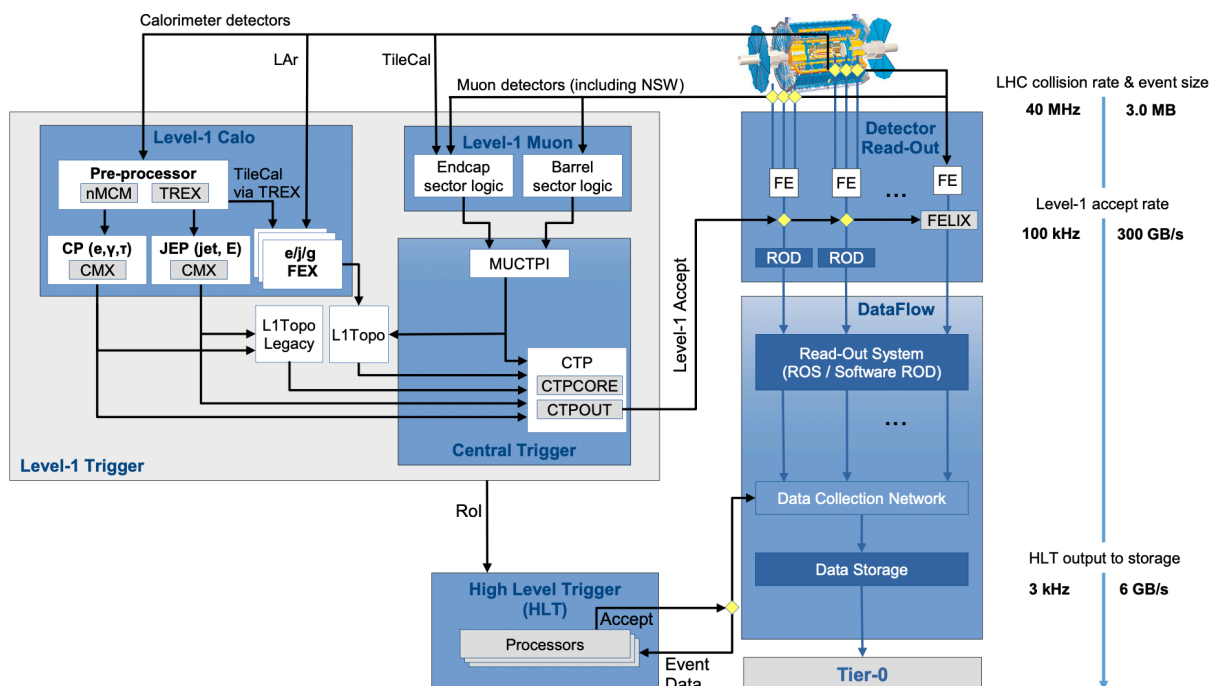


Figure 3-11 Overview of the ATLAS TDAQ system, including Level-1 Calorimeter, Level-1 Muon, and the Central Trigger^[67].

Chapter 4 Event Simulation and Object Reconstruction in ATLAS Experiment

Within the ATLAS experiment, the utility of numerical simulations^[69-70] is essential in both experimental configuration and the subsequent data interpretation. Such simulations are meticulously crafted for every stage of the event process, starting from the initial collision of particles to the response of detectors. This methodology is instrumental in facilitating the identification of potential results and constraints, as well as in calibration of experimental parameters.

Given the massive volume of data produced by the ATLAS detector, quantified in petabytes annually, a comprehensive simulation is necessary. This framework establishes a robust analytical framework, ensuring the alignment of experimental results with theoretical predictions within defined statistical limits. The reliability of the simulation of the entire event cycle is critical as it refines analytical methods and optimizes detector configurations. Therefore, a high level of experimental precision is preserved, contributing to a more reliable investigation of particle physics within the constraints of the Standard Model and beyond.

The core component of the simulation framework is the ATHENA program^[71], which is integrated in the ATLAS computational framework^[72] and powered by the Geant4 toolkit^[73-74]. This simulation process is technically divided into several discrete phases as follows:

- **Event Generation** Event generation within the ATLAS experiment is a foundational stage. It is focused on the production and subsequent decay of particles, incorporating both the calculation of Matrix Elements (ME)^[75] and the dynamics of Parton Shower (PS)^[76] and hadronization^[77]. Generated events are systematically filtered and adhere to the HepMC^[78] standard format, ensuring only those events that satisfy criteria such as leptonic decay or specific missing energy thresholds are retained. This stage predominantly manages prompt decays, especially those involving the electroweak bosons Z and W . Particles are classified as "stable" in the simulation if they traverse into the detector, while the emphasis in event generation is placed on modelling immediate decays. Consequently, the geometry of detector is not a consideration at this point in the event generation process. Operational protocols dictate that each simulated dataset

be assigned a unique set of identifiers. Jobs, runs, and event numbers are cataloged with precision to streamline subsequent analysis. This meticulous approach to event generation not only replicates theoretical particle interactions but also sets the stage for intricate detector simulation and deeper analysis, ensuring adherence to SM predictions and aiding in the search of new physics discoveries.

- **Detector Simulation** In the detector simulation phase of the ATLAS experiment, Geant4 software^[73-74] models the path of particles through the detector and documents the deposit energy as "hits" in sensitive areas. It is a crucial step for understanding how particles interact with the detector materials.
- **Truth Information** Truth information records the precise history of particle interactions and decays during the event generation and simulation. Such kind of information is vital for analyzing and interpreting the data, as it provides a detailed account of the simulated events, including critical processes like photon conversions in the inner layer of detector.
- **Digitization** In the phase of digitization^[79], the simulation output "hits" are transformed into discernible detector signals, such as voltage or time. This stage incorporates the pile-up effect, ensuring computational efficiency and mirroring real-life detector scenarios. The output of digitization is encapsulated in a Raw Data Object (RDO), which differs from the native bytestream format of the detector by including truth information.
- **High-Level Trigger and Reconstruction** Both the High-Level Trigger (HLT) and the reconstruction processes are integrated into the RDO files. These steps are consistent between simulated and actual data, aside from the truth information which is exclusive to the simulation. During real data acquisition, the HLT typically operates with bytestream files but has the capability to revert RDOs to this format if necessary, maintaining a uniform approach to data analysis.

The standard workflow of the ATLAS experiment is illustrated in Fig. 4–1, with each step and output displayed.

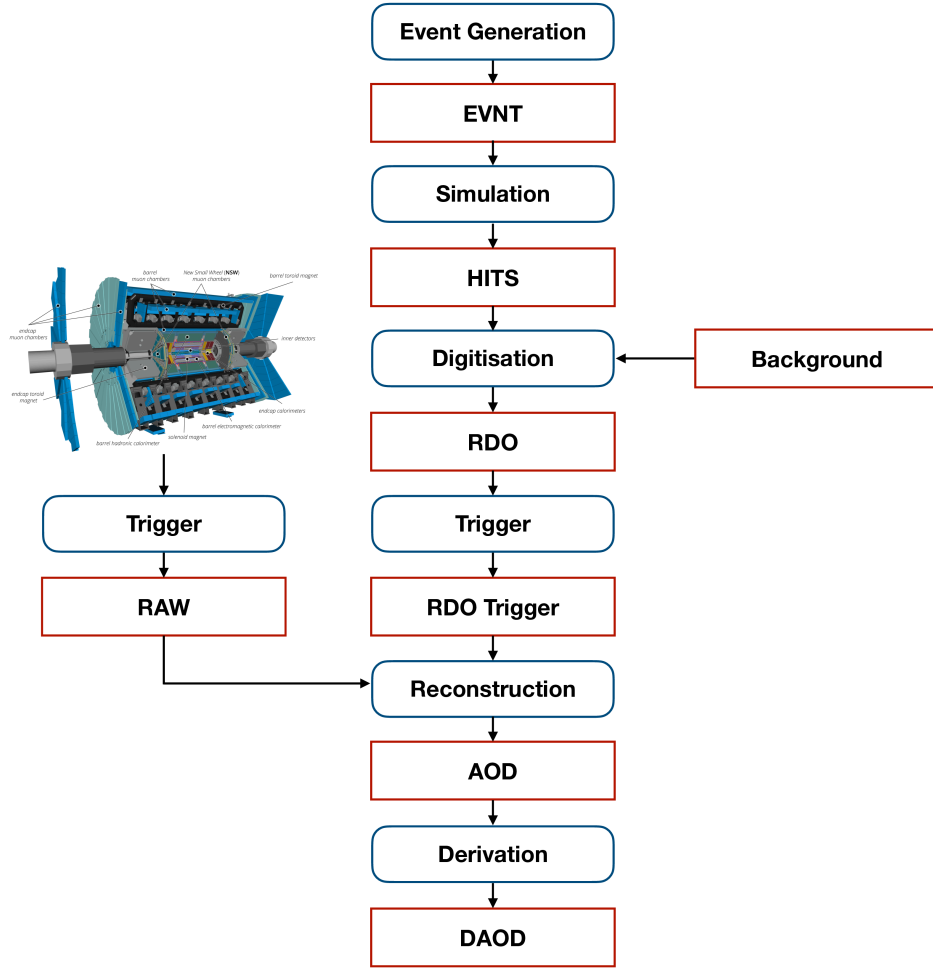


Figure 4–1 The Standard workflow of the ATLAS experiment.

Output format displayed in red blocks, whereas processing steps represented by blue orals. The pileup entering digitization could be additional simulated HITS files, pre-digitized RDO files, or specially processed RAW detector data.

4.1 Production System

The large-scale production system of the ATLAS experiment is integrated with the simulation pipeline, ensuring the distribution and efficient execution of computationally demanding tasks. Utilizing the World-wide LHC Computing Grid (WLCG)^[80], this system orchestrates the partitioning of tasks into multiple jobs, which are calibrated according to their complexity and computational demands. These jobs are designed to execute within the maximal runtime allocation of CPUs, typically extending over two of three days.

The output, encompassing log files, is systematically cataloged within the ATLAS Distributed Data Management (DDM)^[81] system, guaranteeing precise bookkeeping and analysis readiness. To maintain consistency and software reliability, ATHENA software^[71] along with external dependencies like Geant4^[73-74] and generators, are periodically distributed to the production sites and end-users through regular updates and production caches.

Within the WLCG framework, job distribution follows a structured protocol, with an initial test batch of approximately ten jobs to ensure system stability before the remaining jobs are queued. This hierarchical approach allows each stage (generation, simulation, and digitization) to proceed sequentially, ensuring the availability of prerequisite data. Additionally, this system is capable of running concurrent steps for increased efficiency, producing about one million events per day. Modifications to individual jobs are permissible but minimized to maintain uniformity across the system. Adjustments may include random number seeds, generator configurations, detector geometry, and introducing specialized options for specific simulation needs.

Overall, this production system equips ATLAS with the capability to manage its complex simulations effectively, optimizing the use of distributed computational resources for the production of high-quality simulated datasets. This is vital for the experimental goal of probing the frontiers of particle physics.

4.2 Event Simulation

4.2.1 Event Generation

4.2.1.1 General Introduction to Event Generators^[82]

General-Purpose Monte Carlo (GPMC) generators, such as HERWIG^[83-84], PYTHIA^[85-86], and SHERPA^[87], are essential for modelling the complex phenomena that occur during high-energy particle collisions. These tools fulfill a dual role in that they act as the theoretical instruments for exploring the nuances of Quantum Chromodynamics (QCD) beyond the field of fixed-order perturbation theory, and they serve as practical tools for data analysis in experimental physics. GPMC generators operate across various scales, from perturbative where they apply QCD to model hard scattering processes, to non-perturbative scales that manage the transition to hadron formation. The structure of GPMC generators comprises four key

components, each crucial for simulating distinct aspects of particle collisions:

- **Short-Distance, Perturbative Phenomena** At sub-femtometer scales, GPMC generators use perturbative QCD to simulate hard scattering events. Fixed-order calculations for scattering processes are conducted using Matrix Element (ME)^[75], which set the stage for subsequent parton showers (PS)^[76,88] that model the cascading effect of gluon and quark emissions at lower energies. Additional mechanisms like Initial-State Radiation (ISR) and Final-State Radiation (FSR) are factored in to capture emissions surrounding the main scattering events.
- **Non-perturbative Transition** In regions where perturbative techniques do not suffice phenomenological models such as the Lund String or Cluster models are utilized to describe the transformation from quarks and gluons into hadrons.
- **Soft Hadron Physics Model** For the simulation of non-perturbative, larger-scale interactions, GPMC generators integrate models that depict the minimum-bias interactions and underlying events. These models are also equipped to handle soft physics phenomena such as Bose-Einstein correlations and color reconnection.
- **MC Uncertainty Estimates and Tuning** To ensure precision and accuracy, GPMC generators offer methods for uncertainty quantification and parameter tuning, which are fundamental for the integrity and validation of the simulation outputs.

In the simulated pp collision from PYTHIA illustrated in Fig. 4–2, simplifications are made to enhance comprehension and visualization. These include a streamlined number of parton shower branchings and a pared-down representation of final-state hadrons. Recoil effects and weak decays of light-flavor hadrons are typically omitted to reduce diagrammatic complexity. These event generators are indispensable for the simulation, analysis, and interpretation of collision events.

4.2.1.2 Specialized Application in LHC Physics

Within the area of high-energy particle physics, specialized event generators enhance the capabilities of general-purpose Monte Carlo (GPMC) systems, like HERWIG^[83-84] and PYTHIA^[85-86], by providing deeper theoretical insights into Quantum Chromodynamics (QCD). These generators play a pivotal role in both advancing perturbative computations and facilitating sophisticated data analysis and experimental configuration.

EvtGen^[89], developed through the CLEO collaboration, has been instrumental in offering

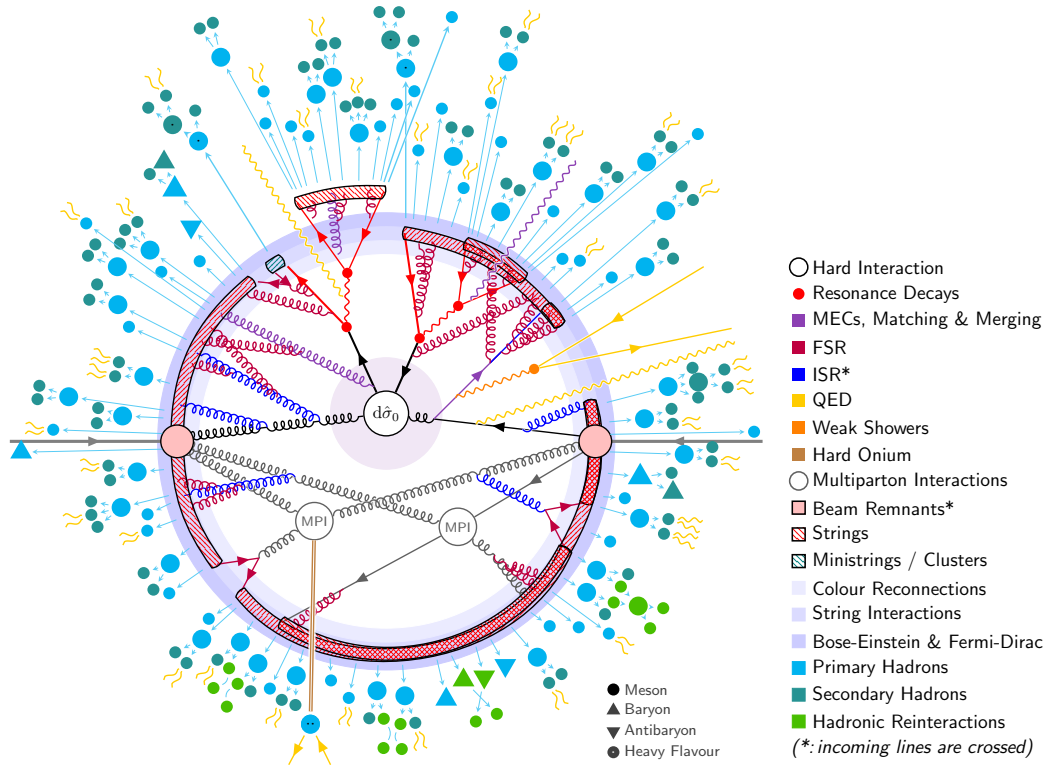


Figure 4-2 Schematic overview of a $pp \rightarrow t\bar{t}$ event as simulated by the PYTHIA software, with modifications for clarity.

1. Shower branchings and final-state hadrons are presented in a reduced number, differing from a full PYTHIA simulation.
2. Recoil effects are not shown to scale.
3. The decay processes of light-flavor hadrons are not included, which portrays the K_S^0 meson as stable for example.
4. The diagram inversely illustrate incoming momentum (represented as $p \rightarrow -p$), whereas Initial State Radiation (ISR) and beam remnant directions are outward-facing to simplify diagrammatic complexity.

This convention is adopted to prevent the intersection of beam remnants and ISR emissions in the central region for clarity.

detailed description in B meson and hadron decays, thereby augmenting the GPMCs and improving their default capabilities. This tool has been particularly beneficial for the researches into B decays in ATLAS experiment, offering specialized simulations that incorporate angular correlations, crucial for calculating acceptance rates for B meson decay modes. Moreover, MC@NLO^[90] stands out for its application of NLO QCD perturbative theory to evaluate hard scattering events, enabling a more precise representation of event kinematics. This is particularly relevant for top quark events, allowing for a more accurate portrayal of their mo-

momentum distributions. The defining characteristic of MC@NLO is its inclusion of one-loop corrections, which introduce events with both positive and negative weights, a factor that necessitates careful consideration in subsequent analyses.

Parton Distribution Functions (PDF)^[91] are essential components for all event generators, providing a mathematical description of the momentum distribution of the partons (quarks and gluons) inside protons. The ATLAS experiment utilizes the Les Houches Accord PDF Interface (LHAPDF)^[92] library, a robust and extensive repository of PDFs, with the default being the CTEQ PDFs^[93-94]. Notably, while MC@NLO utilizes NLO PDFs, other generators commonly employ Leading Order (LO) PDFs. The choice of PDFs is intrinsically related to the tuning parameters associated with the initial state radiations^[95-96]. Given the dependence of system components, different PDFs may lead to discrepancies in simulation results. Consequently, any adoption of a PDF set necessitates a concurrent adjustment for the parameters of event generator to maintain the consistency of the results. The output from these generators are recorded to the Les Houches Event (LHE) format^[97-98], ensuring seamless integration and facilitating complex simulation workflows.

The HepMC^[78] event record is a format that preserves the Monte Carlo truth, as it is a detailed list of all particles involved in the simulated collision. These records distinguish between particles from the initial collision and those from secondary processes, providing a comprehensive account which is vital for calibration and validation of the simulations against the actual detector response. Such detailed record-keeping enables a nuanced understanding of the underlying physical processes, crucial for the optimization of ATLAS simulations and validation of specific event performances.

4.2.2 Enhancing ATLAS event generation: The TestLHE package

4.2.2.1 Overview of Les Houches Event (LHE) files^[98]

In high energy physics (HEP), simulations of particle collisions play a crucial role in exploring fundamental interactions and predicting experimental outcomes at facilities such as LHC. These simulations encompass multiple stages with specialized softwares. To facilitate seamless data transfer between these stages, the Les Houches Event (LHE) file^[98-99] format was established, providing a standardized and versatile framework for storing and exchanging event information.

LHE files encapsulate comprehensive information about simulated particle collisions, including initial conditions, intermediate states, and the final particle produced. This standardized format is pivotal for transmitting data from matrix element generators^[75,100], which computes the probabilities of various collision outcomes, to general-purpose event generators and other simulation tools. The ability to validate theoretical models, optimize detector configurations, and analyze experimental data by referencing these simulations underscores the critical utility of LHE files.

The LHE file contains the header, initialization, and event information for different specific purposes, all formatted in an XML-based structure for clarity and flexibility. Below is an example illustrating the structure of an LHE file^[98]:

Header section The header section contains metadata about the simulation, with details about physics processes involved.

```
<LesHouchesEvent version="3.0">
  <header>
    <generator name="" version="" />
    <processes>
      individually designed tags
    </processes>
  </header>
```

Initialization section The initialization section provides details about the initial state of the beams and the cross-section information.

```
<init>
IDBMUP (1) IDBMUP (2) EBMUP (1) EBMUP (2) PDFGUP (1) PDFGUP (2) PDFSUP (1) PDFSUP (2)
IDWTUP NPRUP
  XSECUP (IPR) XERRUP (IPR) XMAXUP (IPR) LPRUP (IPR)
</init>
```

The initial variables pertain the two incoming beams: identifies(IDBMUP), energies(EBMUP), and the PDF set utilized(PDFGUP, PDFSUP). The IDWTUP specifies the weighting strategy employed, and the remaining variables define a set of NPRUP individually identified processes, accompanied with cross-section information and an integer label for each (XSECUP, XERRUP, XMAXUP, LPRUP).

Event section Each event block within the LHE file contains detailed information for a single event, including both general event and specific particle information. The event section is structured to repeat for each event, providing a comprehensive record of all simulated events.

```
<event>
NUP IDPRUP XWGTUP SCALUP AQEDUP AQCDUP
  IDUP(I) ISTUP(I) MOTHER(1,I) MOTHER(2,I) ICOLOR(1,I) ICOLOR(2,I)
  PUP(1,I) PUP(2,I) PUP(3,I) PUP(4,I) PUP(5,I) VTIMUP(I) SPINUP(I)
</event>
```

NUP represents the number of particles in this event. The event is characterized by: event weight (XWGTUP), scale (SCALEUP), and coupling constants for QED and QCD (AQEDUP, AQCDUP). Each particle is described by several parameters: particle identity using PDG number (IDUP), status (ISTUP), mother particles (MOTHER), color (ICOLOR), four-momentum and mass (PUP), proper lifetime (VTIMUP), and spin (SPINUP).

4.2.2.2 Implementaion of TestLHE package

The TestLHE package^[101] is essential for validating LHE files during the MC central production, ensuring data integrity and consistency within the ATHENA framework^[71]. It performs thorough checks on both the format and content of LHE files during event generation.

Initially, the package verifies the existence and accessibility of LHE files using the Xerces-Parser tool. It then validates the format by checking that event information and particle information, to ensure that no NaN or infinite values exist. Additionally, all particles should have positive energy and mass values, issuing warnings for any discrepancies. The TestLHE package ensures particle consistency by verifying that the number of particles specified matches the actual entries. It conducts physical consistency checks, confirming energy and momentum conservation, checking for tachyonic particles and valid PDG IDs, throwing warnings as needed. Weight information is also scrutinized to ensure uniqueness, proper order, and absence of spaces or special characters, with consistency checks across initialization and event blocks.

Throughout the processes, the package generates output messages and warnings for anomalies without crashing the job. Over time, persistent issues may lead to warnings being con-

verted into errors to enforce stricter quality control. The TestLHE package significantly enhances the reliability and quality of LHE files used in high energy physics simulations, ensuring accurate and well-validated data for subsequent analyses.

4.2.3 Detector Simulation and Response^[102]

4.2.3.1 Full Simulation

The full simulation of the ATLAS detector primarily relies on the Geant4^[73-74] simulation toolkit, which models particle interactions within the complex structure of the detector. This simulation is pivotal for designing experiments and interpreting the results accurately, as it predicts particle behavior in response to various detector components, as illustrated in Table. 4–1.

Subsystem	Materials	Solids	Logical Vol.	Physical Vol.	Total Vol.
Beampipe	43	195	152	514	514
BCM	40	131	91	453	453
Pixel	121	7290	8133	8825	16158
SCT	130	1297	9403	44156	52414
TRT	68	300	357	4034	1756219
LAr Calorimeter	68	674	639	106519	506484
Tile Calorimeter	8	51694	35227	75745	1050977
Inner Detector	243	12501	18440	56838	1824614
Calorimeter	73	52366	35864	182262	1557459
Muon System	22	33594	9467	76945	1424768
ATLAS TOTAL	327	98459	63769	316043	4806839

Table 4–1 Numbers of materials,solids, logical volumes, physical volumes, and total volumes needed for the construction of different components of the ATLAS detector. The term "Inner Detector" encompasses the beampipe, Beam Condition Monitor (BCM), pixel tracker, Silicon Strip Tracker (SCT), and Transition Radiation Tracker (TRT).

The simulation process begins with diverse input options, allowing for extensive configurational flexibility to replicate a broad range of experimental conditions. Geant4 is utilized to meticulously calculate physical interactions such as scattering and energy deposition, ensuring that the simulation outputs closely reflects actual detector response. Outputs from the simulation are detailed and include comprehensive information of particle interactions and trajectories. This information is essential for further analysis and for refining the simulation

based on empirical data. Optimization efforts focus on enhancing computational efficiency and streamlining the simulation to manage resource use effectively without sacrificing accuracy.

Additionally, integrated visualization tools aid in identifying anomalies or deviations in the simulated behaviors, facilitating prompt debugging and adjustments.

4.2.3.2 Fast Simulation

In the ATLAS experiment, fast simulation is developed to efficiently handle large-scale computational demands. These simulations reduce the processing time needed for detailed studies by simplifying certain aspects of particle interaction and detector response, allowing for quicker statistical analyses and theoretical investigation without extensive computational resources required by full simulations. This approach enables the efficient exploration of complex physical scenarios within feasible time frames.

4.2.3.3 Digitization

The digitization process in the ATLAS experiment translates simulated detector hits into electronic signals, termed "digits". These digits are generated based on specific voltage or current thresholds for each detector readout channel within precise time-windows. The process is managed by a Python-based software, ensuring uniformity across all subdetectors and incorporating real-world experimental conditions such as noise and dead channels.

This software is crucial for creating Raw Data Objects (RDOs) from hits, either directly or through intermediate digit stages, and Simulated Data Objects (SDOs) that detail the particle interactions and energy depositions, which are essential for analyzing tracking efficiency and false track rate. Moreover, the digitization accounts for pile-up by integrating signals from multiple particle collisions, ensuring the detector's response closely mimics real interactions scenarios closely. The final conversion from the bytestream format to RDOs is critical for maintaining data integrity and enabling effective reconstruction and analysis.

4.3 Object Reconstruction

4.3.1 Tracks

Track reconstruction^[103-104] in the ATLAS experiment involves analyzing the paths of charged particles from collision events at the LHC. This process is crucial for identifying particle types and measuring their properties. Due to the complexity of particle interactions, particularly in high-energy collisions where particles are densely packed, the reconstruction algorithms must effectively distinguish between closely collimated charged particles. To address challenges in these dense environments, the ATLAS collaboration optimized their reconstruction algorithms to improve accuracy and reduce computational demands. This optimized algorithm is now standard for ATLAS, enhancing the detection and analysis of new physical phenomena. Such a complex process includes several stages^[105] to reconstruct particle trajectories from raw detector hits.

- **Clusterization** In the ATLAS experiment, charged particle reconstruction is performed using connected component analysis (CCA), which clusters measurements from pixel and SCT detectors to create space-points. These points represent the trajectories of charged particles as they pass through the detector. Clusters are formed from adjacent pixel charges and are crucial for determining the path of particles. Clusters are classified based on their charge sources: single-particle clusters come from individual particles, while merged clusters arise from multiple particles. Multiply used clusters, which contribute to several track reconstructions but do not satisfy the merged criteria, are also classified. This clustering is vital for the accurate reconstruction of particle trajectories allow for precise particle tracking and data analysis in the ATLAS detector especially in dense environments.
- **Iterative combinatorial track finding** In the ATLAS experiment, track reconstruction is initiated by forming track seeds from a combination of space-points, which are instrumental in optimizing the estimation of particle trajectories and momentum. The integrity of these seeds is contingent upon the origin of the space-points within the detector array, with enhancements achieved through a strategic application of additional compatible space-points and refinement via a Kalman filter^[106]. This meticulous approach facilitates a track reconstruction efficiency exceeding 99% for primary particles, efficiently distinguishing legitimate tracks from those formed by arbitrary

combinations. The methodology includes a pivotal stage of resolving ambiguities, addressing overlaps or misassigned space-points, all while maintaining adherence to the computational constraints prescribed for event reconstruction.

- **Track candidates and ambiguity solving** The refinement of track candidates is accomplished through an ambiguity solver, which assesses each candidate based on a meticulously defined track score. This score is crucial for prioritizing higher quality tracks, utilizing measures such as intrinsic resolutions and expected cluster multiplicities to distinguish likely particle trajectories from potential misassignments. Emphasis is placed on energetic tracks by incorporating the logarithm of the track momentum into the score, which systematically favors tracks with higher potential for accuracy.

The ambiguity solver rigorously controls the assignment of clusters to track candidates, particularly focusing on clusters that are utilized by multiple tracks. To enhance the precision of track reconstruction, the policy restricts cluster sharing to no more than two tracks. A track candidate that fails to adhere to stringent criteria, including possessing more than two shared clusters, or failing to satisfy baseline quality standards such as a minimum transverse momentum (p_T) of 400 MeV, specific impact parameter limits, and the requisite number of pixel and SCT clusters is disqualified.

This methodology rigor ensures that only the most probable track candidates are advanced for further analysis, thereby maintaining high reconstruction efficiency and optimal utilization of computational resources within the experimental framework. An overview of the ambiguity solving procedures is shown in Fig. 4–3

- **Neutral-network pixel clustering** An artificial neural network (NN)^[107] is utilized to identify merged clusters from particle interactions. This NN leverages deposited energy and pixel position data, enhanced by the incident angle from track candidates, achieving an identification accuracy about 90% for two-particle clusters and 85% for three-particle clusters. However, the NN struggles with clusters involving more than three particles and cannot separate individual energy contributions within merged clusters. To minimize misidentification, the NN is only applied when a cluster is contested by multiple track candidates, thus reducing errors and optimizing the reconstruction process under existing computational constraints.
- **Track fit** Within the ATLAS experiment framework, selected track candidates are sub-

jected to a detailed fitting process post-ambiguity solver intervention, leveraging complete datasets to maximize computational efficiency. This approach minimizes the CPU demand by postponing the intensive fitting process. Furthermore, neural networks enhance the accuracy of cluster localization and uncertainty by predicting particle intersection points and the number of contributing particles. These enhancements are crucial for refining the alignment of detected and computed cluster positions, especially in cases involving merged clusters, thereby improving the precision of the resulting track parameters.

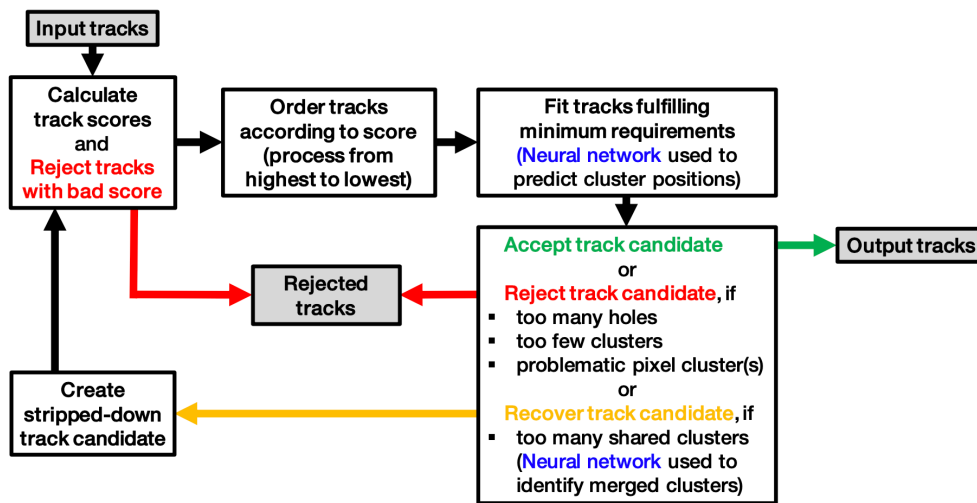


Figure 4–3 Diagram illustrating the progression of track candidate through the ambiguity solver.

4.3.2 Electrons

4.3.2.1 Electron reconstruction

The foundation of the electron and photon reconstruction in the ATLAS experiment is the topological cell clustering algorithm^[108]. Modifications to this reconstruction algorithm are designed to enhance the detection of electrons and photons specifically within the Inner Detector acceptance but do not extend to electrons in regions where $|\eta| > 2.5$, which are already effectively reconstructed using a topo-cluster-based approach. The subsequent section provides a concise overview of topo-cluster formation within the ATLAS calorimeter system and details how clusters from the existing topo-clustering algorithm are adapted for use in

the new reconstruction framework.

This updated approach leverages advanced clustering techniques to isolate and identify electron and photon signals more precisely, enhancing the overall resolution and efficiency of the detector system. The integration of these clusters with track data from the Inner Detector helps in accurately tracing the path and origin of detected particles, crucial for analyses that require high granularity and spatial resolution. This methodology is essential for maintaining the reliability of particle identification and measurement in the complex environment of high-energy collisions in ATLAS experiment, and supporting a wide range of physics investigations. Fig. 4–4 provides a conceptual illustration that depicts the path of electron through various components of the detector, whereas Fig. 4–5 introduces the workflow of the dedicated algorithm applied for electron and photon reconstruction.

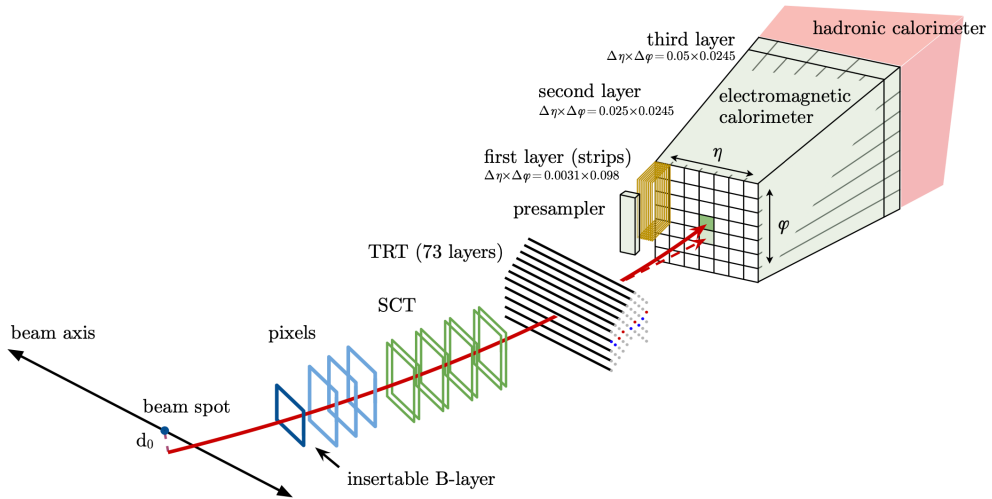


Figure 4–4 Schematic representation of the trajectory of an electron within the detector. The solid red path illustrate the hypothetical path of an electron as it sequentially moves through the tracking system which comprises the pixel detector, the silicon strip detector, and the Transition Radiation Tracker (TRT) and then enters the electromagnetic calorimeter. The dashed red line depicts the path of a photon generated by the interaction of the electron with the material in the tracking system.

The electron reconstruction^[109] is intricately based on the formulation of topological clusters (topo-clusters) within the ATLAS experiment, emphasizing the spatial signal significance from particle interactions. The process is initiated by establishing the cell significance,

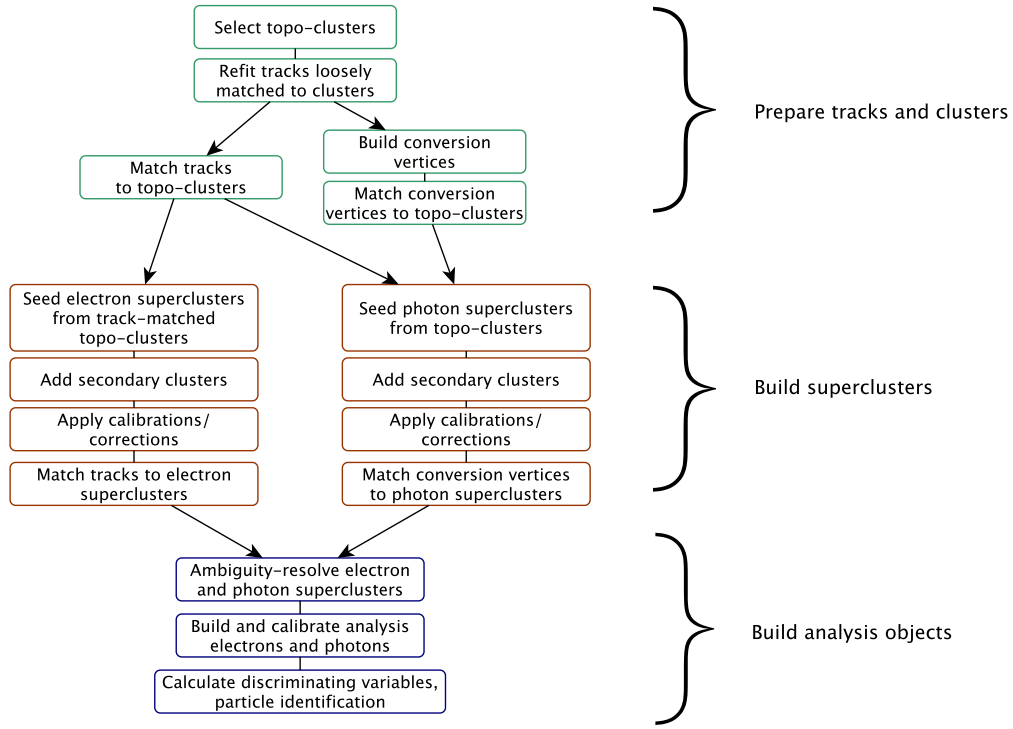


Figure 4–5 Schematic diagram for the electron and photon reconstruction algorithm.

$S_{\text{cell}}^{\text{EM}}$, defined by the ratio:

$$S_{\text{cell}}^{\text{EM}} = \frac{|E_{\text{cell}}^{\text{EM}}|}{\sigma_{\text{noise, cell}}^{\text{EM}}} \quad (4-1)$$

where $|E_{\text{cell}}^{\text{EM}}|$ denotes the absolute energy of the cell on the electromagnetic (EM) scale, and $\sigma_{\text{noise, cell}}^{\text{EM}}$ is the expected noise. Proto-clusters are formed when cells exceed a significance threshold of four, expanding to include neighboring cells that surpass a secondary significance threshold of two.

These proto-clusters evolve through iterative merging as neighboring cells with energies above the noise threshold are incorporated. They are termed topo-clusters once stability in cluster formation is achieved. For clusters presenting multiple potential electron signals, indicated by several local maxima, fractional cell weights are assigned to enhance the resolution.

These weights are computed using:

$$w_{\text{cell},1} = \frac{E_{\text{clus},1}^{\text{EM}}}{E_{\text{clus},1}^{\text{EM}} + r E_{\text{clus},2}^{\text{EM}}} \quad (4-2a)$$

$$w_{\text{cell},2} = 1 - w_{\text{cell},1} = \frac{r E_{\text{clus},2}^{\text{EM}}}{E_{\text{clus},1}^{\text{EM}} + r E_{\text{clus},2}^{\text{EM}}} \quad (4-2b)$$

where $r = \exp(d_1 - d_2)$, reflecting the relative distances of the cell to the cluster centroids.

Further refinement in identifying electron and photon topo-clusters uses the f_{EM} metric, defined as:

$$f_{\text{EM}} = \frac{E_{\text{L1}} + E_{\text{L2}} + E_{\text{L3}} + w(E_{\text{E4}} + E_{\text{PS}})}{E_{\text{cluster}}}, \quad w = \begin{cases} 1, & 1.37 < |\eta| < 1.63 \\ 0, & \text{otherwise} \end{cases} \quad (4-3)$$

with $E_{\text{L}x}$ represents the cluster energy in layer x of the calorimeter, E_{clus} is the total cluster energy, and $E_{\text{E4}} + E_{\text{PS}}$ accounts for the energy deposited in the presampler (PS) and the additional E_{E4} layer together. This metric assesses the proportion of energy in the cluster attributable to electromagnetic showers, with w adjusted based on the pseudorapidity region of the cluster to account accurately for electron and photon energy deposition.

A low energy threshold of 400 MeV is implemented to exclude clusters arising from background noise and pile-up interactions. The optimization of $f_{\text{EM}} > 0.5$, derived from extensive Monte Carlo simulations, strategically balances effective electron identification and the minimization of false positives.

In the ATLAS experiment, electron and photon track reconstruction begins by identifying electromagnetic (EM) clusters based on specific shower shape requirements. These clusters define Regions of Interest (ROI) where standard track pattern reconstruction takes place. If initial pattern recognition fails, it is supported by a modified Kalman filter approach, allowing for up to 30% energy loss at material intersections. Tracks loosely matched to EM clusters are then refined using the Gaussian Sum Filter (GSF), improving track parameter estimation by addressing the nonlinear energy losses due to bremsstrahlung.

The construction of electron superclusters involves a systematic approach:

- **Seed Cluster Identification** EM topoclusters are utilized to act as seed clusters. These need to have a minimum E_T of 1 GeV and must be associated with a track that has at least four hits in the silicon trackers.

- **Satellite Cluster Identification** Potential satellite clusters are identified based on their proximity to the seed cluster. Spatial criteria include that a cluster is categorized as a satellite if it lies within a $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ window around the seed cluster barycenter, whereas a cluster will also be considered as a satellite for electron if it lies within a $\Delta\eta \times \Delta\phi = 0.125 \times 0.300$ window and its "best-matched" track aligns with the seed cluster.

The refined tracks are precisely matched to EM clusters based on stricter spatial criteria in η and ϕ , prioritizing those with significant hits in the pixel detector and the closest alignment in terms of the ΔR metric. This ensures accurate track matching, which is essential for reliable electron identification. Additionally, cluster energy calibration utilizes the Interquartile Energy (IQE) measure, defined as:

$$IQE = \frac{Q_3 - Q_1}{1.349} \quad (4-4)$$

where Q_1 and Q_3 are the first and third quartiles of the $E_{\text{calib}}/E_{\text{true}}$ distribution, the normalization factor of 1.349 ensures that the IQE for a Gaussian distribution is equivalent to its standard deviation. This formula standardizes the IQE to the standard deviation of a Gaussian distribution, facilitating precise energy measurements within the clusters.

4.3.2.2 Electron identification

Electron identification^[110] in the ATLAS experiment utilizes a sophisticated likelihood-based method (LH) to distinguish prompt electrons from other similar particles such as jets or non-prompt electrons. This method integrates a series of measurements from both the tracking system and calorimeter system into probability density functions (PDFs). The likelihoods (LH) for signal (L_S) and background (L_B) are calculated using the equation:

$$L_{S(B)}(x) = \prod_{i=1}^n P_{S(B)}, i(x_i), \quad (4-5)$$

where $P_{S(B)}, i(x_i)$ represents the value of the signal (background) PDF for each measured quantity at value x_i . To assist in decision-making, a discriminant $d_L = \frac{L_S}{L_S + L_B}$ is computed, which is then transformed using an inverse sigmoid function:

$$d'_L = -\tau^{-1} \ln(d_L^{-1} - 1), \quad (4-6)$$

with τ set to 15^[111], to facilitate the setting of thresholds by stretching the d_L values over a more manageable range.

Table 4–2 summarizes quantities for electron identification, various metrics are presented that are instrumental for the identification of prompt electrons. Columns titled "Rejects" denotes the efficacy of metrics in distinguishing between prompt electrons and both light-flavour (LF) jets and non-prompt electrons from semi-leptonic decays of hadrons containing heavy-flavour (HF) quarks (b- or c-quarks). The "Usage" column indicates that "LH" corresponds to the probability density function (PDF) employed in the logistic regression models L_S and L_B , as defined in Equation 4–5, and "C" signifies direct application of the metric as a selection criterion. The notations like 3×3 , 3×5 , 3×7 , and 7×7 designate the specific area in $\Delta\eta \times \Delta\phi$ with units of 0.025 by 0.025.

Metrics instrumental for LH calculations, such as details of calorimeter shower shapes and particle energies, are selected specifically for their sensitivity and incorporated into L_S and L_B . Metrics that may not be distinctly powerful enough for cut-based methods but provide valuable information are included in the LH method, thus offering a more holistic evaluation of electron candidates. This approach not only consider individual measurements but also collectively assimilates the information from all variables.

The PDFs for LH identification are derived from simulation, binned according to the electron candidate's energy and pseudorapidity, and smoothed using kernel density estimation to minimize statistical noise. Corrections are applied to these PDFs to account for any discrepancies between simulation and actual data, ensuring the LH method accurately reflects the true conditions experienced within the detector.

Operational points for LH-based electron identification, which are VeryLoose, Loose, Medium, and Tight, are defined to cover different signal efficiencies and background rejection needs required by physics analyses. These points are determined using finely binned data, and adjustments are made to ensure smooth transitions between different electron E_T bins, maintaining consistent identification efficiency across varying experimental conditions.

Fig. 4–6 consists of two plots that display the efficiencies of different electron identification methods during the 2015 – 2018 Run2 period at the LHC for $Z \rightarrow e^+e^-$ events. The left plot depicts these efficiencies as function of electron transverse energy E_T , and the right plot examines the efficiencies across varying electron pseudorapidity (η) ranges. It not only aggregates data but also highlights the results from specific efficiency assessment methods, particularly the Z-mass and Z-isolation techniques. Employing the tag and probe

Type	Description	Name	Rejects			Usage
			LF	γ	HF	
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	R_{had1}	x	x		LH
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	x	x		LH
Third layer of EM calorimeter	Ratio of the energy in the third layer to the total energy in the EM calorimeter. This variable is only used for $E_T < 80$ GeV, due to inefficiencies at high E_T , and is also removed from the LH for $ \eta > 2.37$, where it is poorly modelled by the simulation.	f_3	x			LH
Second layer of EM calorimeter	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy, and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells centred at the electron cluster position	$w_{\eta 2}$	x	x		LH
	Ratio of the energy in 3×3 cells over the energy in 7×7 cells centred at the electron cluster position	R_ϕ	x	x		LH
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centred at the electron cluster position	R_η	x	x	x	LH
First layer of EM calorimeter	Shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi = 0.0625 \times 0.2$, corresponding typically to 20 strips in η , and i_{max} is the index of the highest-energy strip, used for $E_T > 150$ GeV only	w_{stot}	x	x	x	C
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies	E_{ratio}				LH
	Ratio of the energy in the first layer to the total energy in the EM calorimeter	f_1				LH
Track conditions	Number of hits in the innermost pixel layer	n_{Blayer}				C
	Number of hits in the pixel detector	n_{Pixel}				C
	Number of hits in the pixel and SCT detectors	n_{Si}				C
	Transverse impact parameter relative to the beam-line	d_0				LH
	Significance of transverse impact parameter defined as the ratio of d_0 to its uncertainty	$\frac{ d_0 }{\sigma(d_0)}$	x			LH
	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee	$\Delta p/p$				C
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT			x	LH
Track-cluster matching	$\Delta\phi$ between the cluster position in the first layer and the extrapolated track	$\Delta\phi_1$	x	x		LH
	$\Delta\phi$ between the cluster position in the second layer of the EM calorimeter and the momentum-rescaled track, extrapolated from the perigee, times the charge q	$\Delta\phi_{\text{res}}$	x	x		LH
	Ratio of the cluster energy to the track momentum, used for $E_T > 150$ GeV only	E/p	x	x		C

Table 4–2 Overview and classification of metrics used for electron identification^[110].

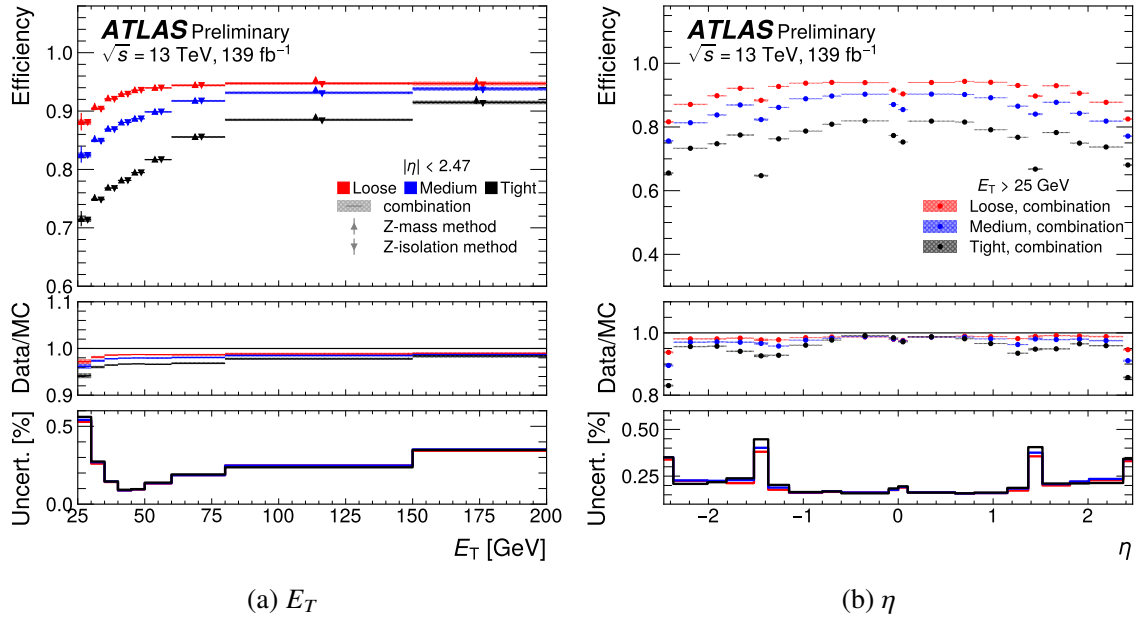


Figure 4-6 Efficiency distributions of electron at various identification working points^[112].

method with two electrons, as opposed to photons, facilitates differentiation between signals. Electrons, with charge, provide clearer tracking and identification signals compared to neutral photons, thus simplifying the validation and measurement processes across these plotted ranges. The inclusion of error bands representing statistical and systematic uncertainties adds a comprehensive dimension to the data quality. A significant aspect of the η plot is the reduced efficiency within the transition zone between the electromagnetic calorimeter barrel and endcap, specifically from $1.37 < |\eta| < 1.52$. This strategic adjustment, employing tighter selection criteria, is designed to specifically enhance background rejection in the transition zone between the electromagnetic calorimeter barrel and endcap, where standard methods are less effective at distinguishing between signal and noise.

4.3.2.3 Electron isolation

Electron isolation constitutes a pivotal aspect of particle physics research, particularly within the ATLAS experiment at the LHC. The isolation of electrons in this study is quantified through two primary methodologies: calorimeter-based and track-based isolation variables. These serve as indispensable tools for separating prompt electrons from background processes, a necessity for achieving precision in measurements and investigating heavy res-

onances such as Higgs, W, and Z bosons, where electrons are logically isolated.

Calorimeter-Based Isolation In the calorimeter-based paradigm, isolation quantification involves the summation of transverse energies within a defined cone centered around the electron. This process entails aggregating the transverse energies of topological clusters situated within the electron or photon cluster center's vicinity. Initially, the raw transverse energy ($E_{T, \text{raw}}$) is computed, followed by the application of corrections for energy leakage, pile-up effects, and the subtraction of the electromagnetic particle energy ($E_{T, \text{core}}$). The resultant corrected calorimeter isolation variable E_{coneXX} is expressed as:

$$E_{\text{coneXX}} = E_{T, \text{raw}}^{\text{isolXX}} - E_{T, \text{core}} - E_{T, \text{leakage}}(E_T, \eta, \Delta R) - E_{T, \text{pile-up}}(\eta, \Delta R) \quad (4-7)$$

where $\Delta R = XX$. For electron working points, a cone size of $\Delta R = 0.2$ is conventionally employed.

Track-Based Isolation Conversely, track-based isolation evaluates isolation by considering the transverse momentum of selected tracks within a cone centered around the electron or photon direction. The variable cone size ($p_{\text{varconeXX}}$) for electrons is defined as:

$$\Delta R = \min\left(\frac{10}{p_T [\text{GeV}]}, \Delta R_{\text{max}}^2\right) \quad (4-8)$$

where ΔR_{max} typically assumes a value of 0.2. Tracks must adhere to $p_T > 1$ GeV and $|\eta| < 2.5$ criteria, alongside specific hit requirements within the silicon detectors.

Working point	Calorimeter isolation	Track isolation
Gradient	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with E_T^{cone20})	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with p_T^{cone20})
HighPtCaloOnly	$E_T^{\text{cone20}} < \max(0.015 \times p_T, 3.5\text{GeV})$	-
Loose	$E_T^{\text{cone20}}/p_T < 0.20$	$p_T^{\text{varcone20}}/p_T < 0.15$
Tight	$E_T^{\text{cone20}}/p_T < 0.06$	$p_T^{\text{varcone20}}/p_T < 0.06$

Table 4–3 Summary of electron-isolation operating points and isolation efficiency ϵ_{iso} ^[108].

Table 4–3 summarizes electron isolation strategies and their respective efficiencies. For the "Gradient" operational point, the transverse momentum (p_T) is expressed in GeV units. A cone size of $\Delta R = 0.2$ is utilized for both calorimeter isolation and track isolation methods, with a maximum cone size of $\Delta R_{\text{max}} = 0.2$ designated for track isolation. These specifications

are derived from a simulated $Z \rightarrow ee$ sample, where electrons adhere to Tight identification criteria.

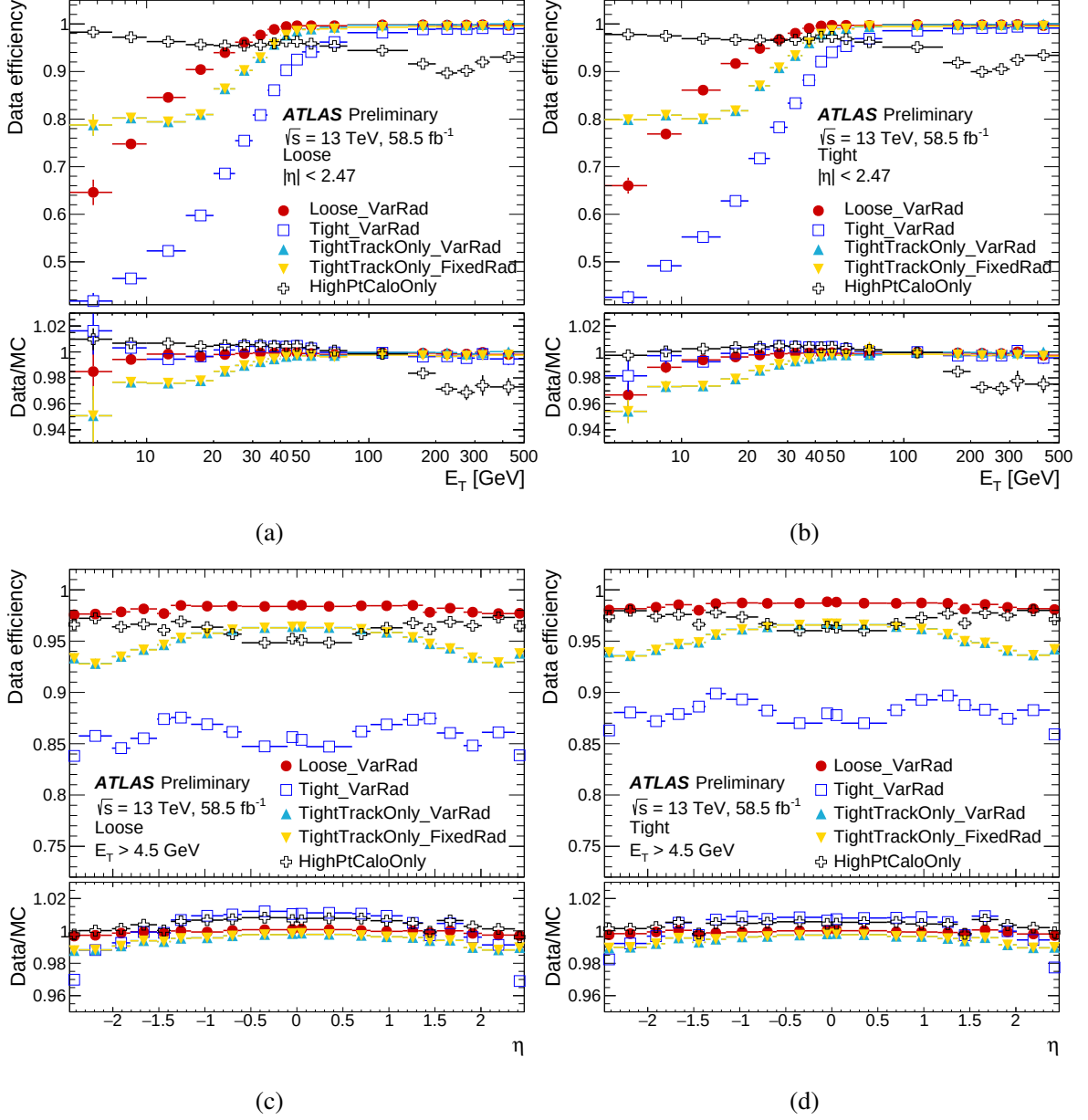


Figure 4-7 Efficiency distributions of electron at various isolation working points^[112].

Furthermore, Fig. 4-7 conducts a comparative analysis of electron isolation efficiencies for $Z \rightarrow ee$ events captured during the 2018 Run2 of the LHC, thereby furnishing valuable insights into the efficacy of isolation methodologies within real experimental settings.

4.3.3 Photons

In the ATLAS experiment, the methodologies for photon reconstruction closely align with those employed for electrons, as both particle types interact similarly within the electromagnetic calorimeter. The foundational approaches to reconstruction and identification for those particles are nearly identical, thereby allowing this discussion to focus directly on the specific identification (ID) and isolation procedures uniquely tailored for photons, without revisiting the common reconstruction algorithms detailed in previous sections.

4.3.3.1 Photon identification

Photon reconstruction and identification in high-energy physics experiments such as ATLAS involves sophisticated techniques to accurately categorize photons based on their interaction within the detector. Photon candidates are classified either as converted or unconverted. Converted photons, which interact with the detector material converting into an electron-positron pair, are identified through EM topo-clusters associated with one or more conversion vertices. In contrast, unconverted photons are identified when no such conversion is detected.

Three principal methods measure photon identification efficiency^[110]:

1. **Radiative Z-decays** Utilize a sample of radiative $Z \rightarrow \ell\ell\gamma$ decays. The efficiency is calculated within specific kinematic constraints, leveraging Monte Carlo simulations to model expected distributions. This method is sensitive to systematic uncertainties from generator modelling.
2. **Matrix Method** Applied to inclusive photon samples to differentiate signal from background, focusing on those passing or failing stringent identification and isolation criteria. This method becomes particularly effective at high transverse energies (E_T) but depends on precise background modelling.
3. **Electron Extrapolation** Transforms electron data from $Z \rightarrow e^+e^-$ decays to simulate photon characteristics. This method uses the invariant mass distribution of electron pairs to distinguish signal from background, providing insights into photon behavior unique to this technique.

These methods, each with its advantages and limitations, are often influenced by the E_T range and data quality. They are combined to provide a robust overall efficiency measure-

ment, crucial for analyses reliant on precise photon identification, such as those conducted by the ATLAS detector at the LHC. This combination mitigates individual method biases, enhancing the reliability of photon-related measurements in particle physics experiments.

The photon identification efficiencies, depicted in Fig. 4–8, are initially quantified through Monte Carlo (MC) simulations. Subsequent adjustments are made to the photon shower shapes to enhance their consistence with the original data^[113]. The ratios of data to MC simulations are then employed to mitigate the discrepancies in identification efficiencies across different bins of transverse energy (E_T) and pseudorapidity (η). These efficiencies are computed using a weighted average of the three methodologies across each $E_T - \eta$ bin.

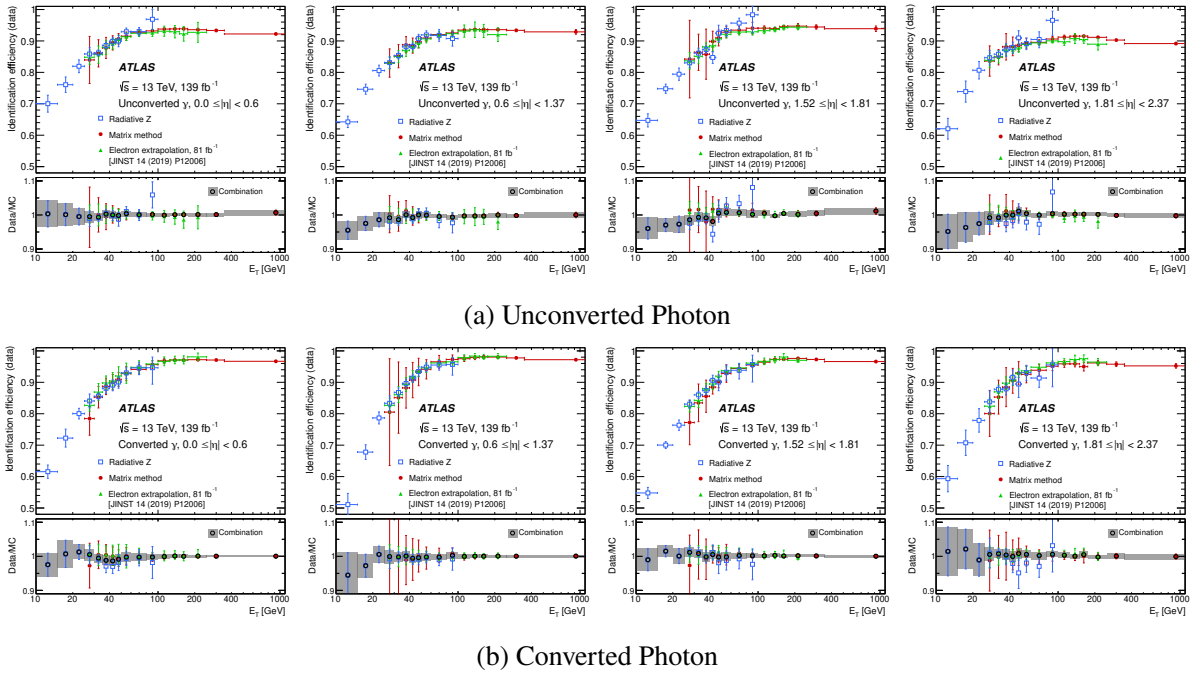


Figure 4–8 Identification efficiencies measured in data for unconverted and converted photons across different η bins^[114].

4.3.3.2 Photon isolation

Photon isolation in the ATLAS experiment is a critical measurement used to distinguish between signal photon and background noise. Photon isolation efficiencies are calculated using both calorimeter-based and track-based isolation variables. These variables assess the separation of the photon from other activity in the detector, thus ensuring the purity of the photon signal. Discrepancies between the results from Monte Carlo simulations and ac-

tual experimental data have necessitated the use of data-driven adjustments. These adjustments correct the mismatches in the peak positions of isolation variable distributions, likely due to inaccuracies in modelling the lateral profile development of electromagnetic showers. Methodologies used for photon isolation efficiency measurements:

Radiative Z Decays This method provides a clean environment for studying photon isolation by leveraging the final-state radiation in radiative Z decays.

Inclusive-Photon events Another approach involves inclusive-photon events, where efficiency measurements are derived by fitting the isolation variable distributions and adjusting for background effects to refine efficiency estimations.

Photon identification working points are crucial benchmarks set to categorize detections into distinct levels of confidence, namely Loose, Medium, and Tight. These criteria are defined based on specific detector responses, such as patterns of energy deposition and track isolation metrics. Each working point delineates a stringent set of parameters that a particle, like a photon or electron, must satisfy to qualify for the classification. This systematic categorization enabled to tailor the analyses to specific precision and sensitivity needs, optimizing the balance between signal enhancement and background suppression.

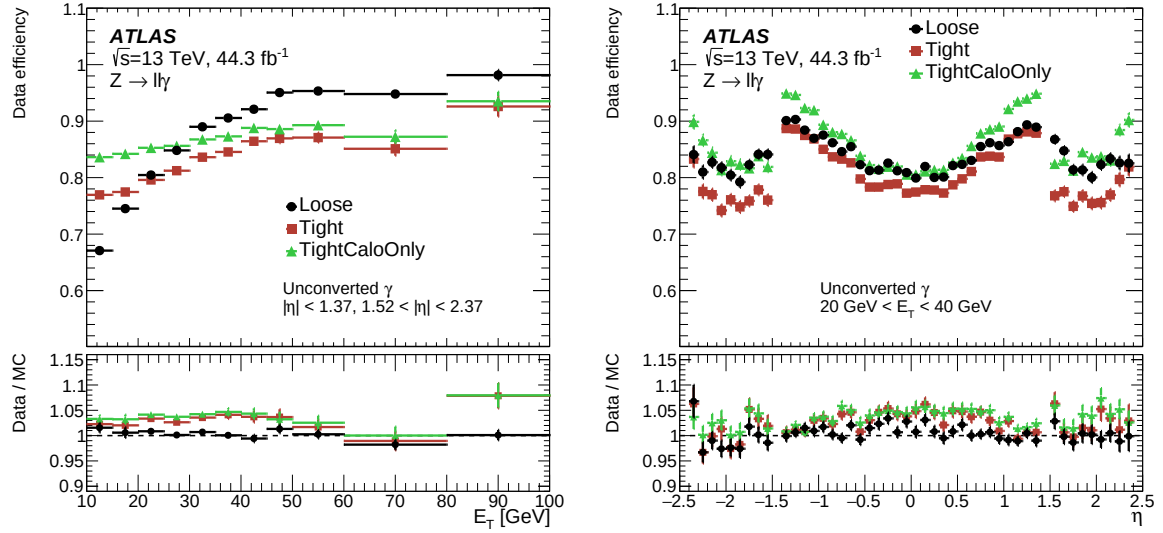
Table 4–4 illustrates three specific operational settings for photon isolation, encompassing both calorimeter and track isolation variables. The research^[110] exposes variances between original observations and simulations regarding the calorimeter-based isolation metrics. These discrepancies are addressed through derived adjustments. The efficiency of these adjustments is subsequently evaluated across two principal photon detector scenarios: radiative Z decays and inclusive photon events.

Working point	Calorimeter isolation	Track isolation
Loose	$E_T^{\text{cone20}} < 0.065 \times E_T$	$p_T^{\text{cone20}}/E_T < 0.05$
Tight	$E_T^{\text{cone40}} < 0.022 \times E_T + 2.45\text{GeV}$	$p_T^{\text{cone20}}/E_T < 0.05$
TightCaloOnly	$E_T^{\text{cone40}} < 0.022 \times E_T + 2.45\text{GeV}$	-

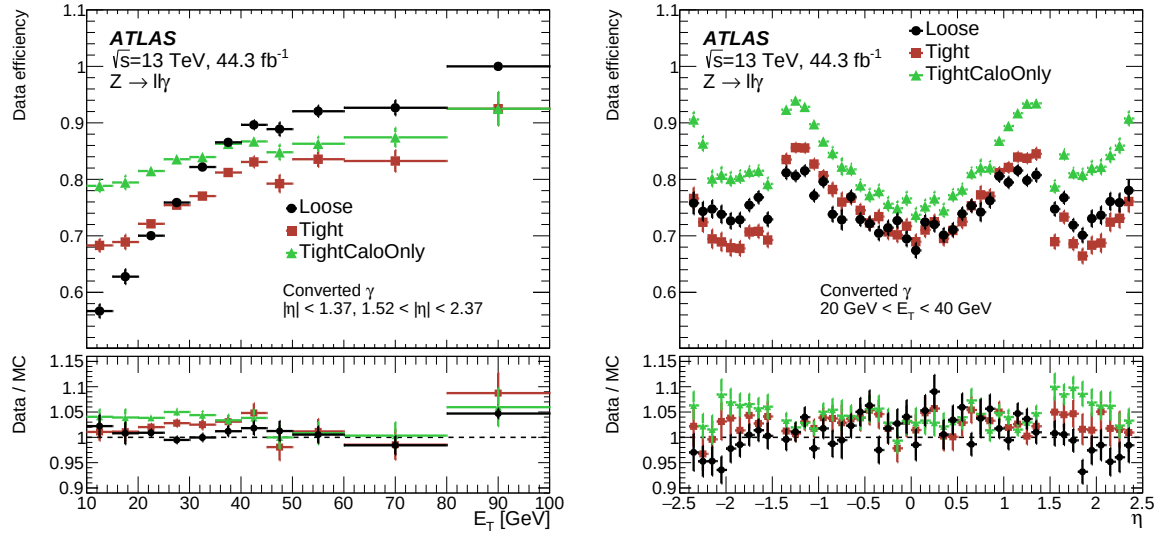
Table 4–4 Summary of photon isolation working points^[110].

Fig. 4–9 illustrates the efficiency of the photon isolation working points estimated from

$Z \rightarrow \ell\ell$ events, for both unconverted and converted photons. The efficiencies are analyzed as functions of photon transverse energy E_T and pseudorapidity (η). The lower panes indicates the ratios of these efficiencies between measured experimental data and simulation, including both statistical and systematic uncertainties.



(a) Unconverted Photon



(b) Converted Photon

Figure 4–9 Isolation efficiencies measured in data for unconverted and converted photons across different E_T and η bins^[110,115].

The efficiency measurements from these methods are combined to enhance the reliability

of the results. Calo-only and track-only photon isolation efficiencies have been found to vary with the transverse energy (E_T) of photon and pile-up activity, necessitating adjustments for systematic uncertainties under different conditions. The combined scale factors derived from these results are crucial for adjusting theoretical models to better align with observed data. These factors improve the accuracy of simulations used in subsequent analyses, ensuring that the experiments can rely on robust and precise photon identification.

4.3.3.3 Optimization on photon ID against electron fakes

Effective discrimination between photons and electrons is challenging due to the similar detection signatures. A schematic illustration is displayed in Fig. 4–10 of the logic of the ambiguity resolution procedure performed within the ATLAS experiment. An "innermost hit" refers to a detection by the nearest functioning pixel to the beam-line along the path of the track. E/p represents the ratio of energy of the supercluster to the momentum of the associated track. R_{conv} denotes the radial distance from the beam-line to the conversion vertex, while R_{firstHit} is the minimum radial distance of any hit on the track or tracks forming a conversion vertex.

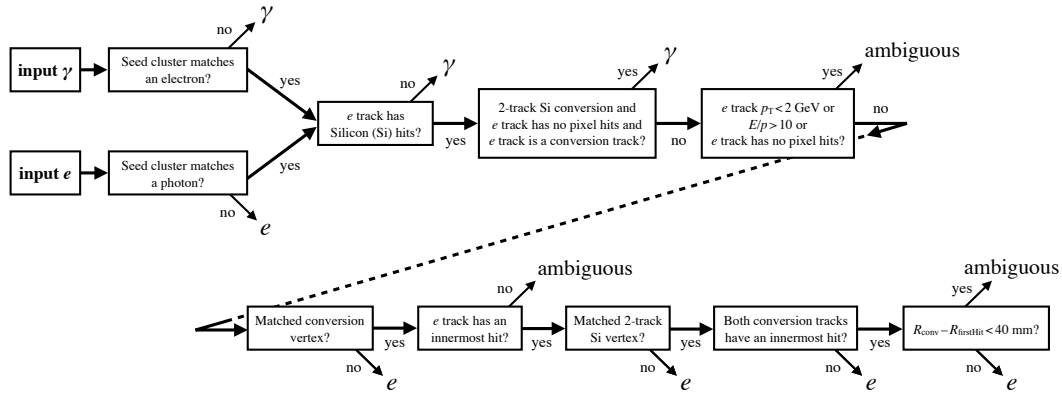


Figure 4–10 Flowchart of the ambiguity procedure for electrons and photons^[110,115].

The differentiation process begins after the construction of electron and photon superclusters, which undergo initial energy calibration and positional adjustments. These superclusters are then assessed for associated tracks and conversion vertices to identify the particle type. To solve ambiguities between photons and electrons, the analysis focuses on the presence of high-quality tracks and photon conversion vertices. A supercluster associated solely with a high-quality track and lacking a photon conversion vertex is typically classified as

an electron. Conversely, a supercluster without an associated high-quality track but with a photon conversion vertex is identified as a photon. The object will be marked as ambiguous when neither condition is definitively met, and requires further analysis tailored to the specific requirements of the experiment.

Following this classification, energy recalibration is performed to ensure precise particle momentum measurement.

4.3.4 Muons

Muon reconstruction is primarily performed using the Inner Detector(ID) and Muon Spectrometer (MS)^[116-117], with additional data from calorimeters to refine track parameters and support energy loss calculations. This comprehensive approach facilitates the identification of muons, leveraging algorithms that analyze tracks and energy deposits to discriminate muons from other particles. Furthermore, muon isolation is critically assessed to ensure that muons are distinct from nearby particle activities, enhancing the accuracy of measurements and reducing systematic uncertainties. These processes collectively enable the efficient detection of muons with high precision, crucial for analyzing proton-proton collision data and studying decay processes involving muons.

4.3.4.1 Muon reconstruction

The muon reconstruction^[118] process within the ATLAS experiment is an intricate procedure that starts with the detection of muon tracks in the Muon Spectrometer (MS). It employs an integration of short straight-line track segments identified at individual MS stations, which are subsequently combined across stations using a Hough transformation^[119]. To establish robust preliminary track candidates, a loose pointing constraint alongside a parabolic trajectory, which accounts for magnetic field interactions, is applied. These trajectories are further refined by merging preliminary tracks with precision measurements of the second coordinate and data from trigger detectors, resulting in sophisticated three-dimensional track candidates.

Subsequent refinement includes a global χ^2 fit of the muon trajectory, integrating additional hits previously unassigned to the original track candidate. This process involves removing outlier hits and updating the track with newly acquired hit information. To resolve ambiguities in track identification, the methodology excludes tracks that share a significant fraction of hits, unless these hits are confined to identical stations and exhibit higher qual-

ity. The final set of tracks undergoes a re-fit incorporating a relaxed impact parameter (IP) constraint and accounts for energy losses in the calorimeters. These tracks are then back-extrapolated to the beamline, where the transverse momentum (p_T) of the extrapolated track is precisely determined at the IP.

The comprehensive muon reconstruction process utilizes detailed detector information from both the Inner Detector (ID) and MS, along with calorimeter data. This leads to several specialized muon identification strategies:

1. **Combined Muons (CB)** Combined muons are identified by matching MS and ID tracks, performing a combined track fit that accounts for energy losses in the calorimeters. For $|\eta| > 2.5$, shorter segments from the pixel and SCT detectors enhance track reconstruction, leading to the specific identification of silicon-associated forward (SiF) muons.
2. **Inside-Out Combined (IO) Muons** Identified by fully extrapolating ID tracks within the MS using a highly selective matching algorithm.
3. **Muon-Spectrometer Extrapolated (ME) Muons** Defined when MS tracks that do not correspond with any ID track are extrapolated to the beamline, thus extending the detector's reach to $|\eta| < 2.7$.
4. **Segment-Tagged (ST) Muons** Require tight angular matching between an ID track extrapolated to the MS and at least one MS segment.
5. **Calorimeter-Tagged (CT) Muons** Identified by extrapolating ID tracks through the calorimeters to locate energy deposits indicative of muons, with a p_T threshold of 5 GeV to manage background contamination at low p_T .

Recent enhancements to this muon reconstruction protocol include^[120]:

- The implementation of a parabolic trajectory in pattern recognition to improve segment matching across different stations.
- The introduction of Silicon-associated Forward (SiF) muons to better utilize the ID near its acceptance boundaries.
- Adjustments to account for alignment uncertainties using constrained nuisance parameters that accurately describe translational and rotational chamber displacements.
- A recalibration of the calorimeter-tagging algorithm to increase purity in regions with limited MS coverage ($|\eta| < 0.1$) and the introduction of a looser working point for

high-efficiency in tag-and-probe studies.

These improvements not only refine the detection and characterization of muons in high-energy collisions but also enhance the capability of ATLAS detector to explore fundamental particle interactions under a variety of experimental conditions.

4.3.4.2 Muon identification

Muon identification within the ATLAS experiment plays a pivotal role in the analysis of collider data, facilitating the selection of high-quality muon candidates post-reconstruction. This selection is governed by stringent criteria that encompass the number of detector hits across the Inner Detector (ID) and the Muon Spectrometer (MS), the accuracy of the track fits, and the compatibility of the measurements between these two detector systems. These criteria are instrumental in effectively distinguishing between prompt muons which originate directly from the primary collision vertex, and non-prompt muons such as emanating from the semileptonic decays of lighter hadrons or from decays of hadrons bearing heavy flavors.

Three selection working points (WPs) for muon identification within the ATLAS experiment: Loose, Medium, and Tight, are defined by several numerical criteria, which vary according to the pseudorapidity ($|\eta|$) and transverse momentum (p_T) of the muon candidates.

The Medium working point, designed to balance efficiency and purity, stipulates that muons must satisfy specific criteria including:

- ID Acceptance: $|\eta| < 2.5$
- Number of Precision Stations: ≥ 2 (Exception: $|\eta| < 0.1$ can have one)
- q/p Compatibility: < 7

The Loose working point encompasses all criteria of the Medium WP, with additional inclusivity for specific types of muons:

- For $|\eta| < 0.1$: Includes CT and ST muons
- For $p_T < 7$ GeV and $|\eta| < 1.3$: Includes IO muons with only one precision station

This WP aims to enhance detection efficiency by approximately 20% for muons with $3 \text{ GeV} < p_T < 5 \text{ GeV}$, and by 1% or 2% for $p_T > 5 \text{ GeV}$.

Conversely, the Tight WP imposes stringent requirements for the quality of track fit, maintaining a χ^2/ndf less than 8, and optimized q/p and ρ values, tailored based on the p_T and η of muon. The Tight WP provides substantial background reduction, more than 50% relative to the Medium WP, and an efficiency loss of about 6 % for $6 \text{ GeV} < p_T < 20 \text{ GeV}$.

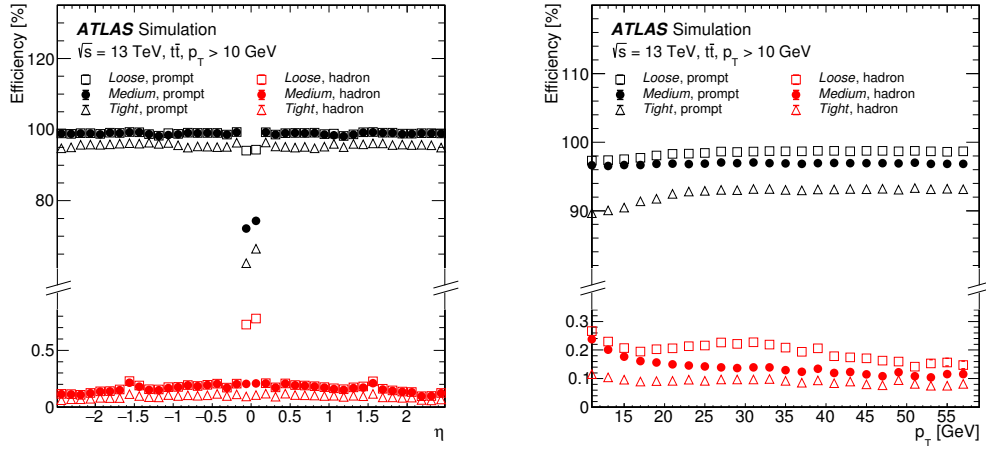


Figure 4-11 Efficiency plotted against pseudorapidity (η) and transverse momentum (p_T) for the Loose, Medium, and Tight working points in $t\bar{t}$ events^[118,121].

In Fig. 4-11, the efficiencies of different working points (WPs) are graphically represented against pseudorapidity (η) and transverse momentum (p_T) with simulated $t\bar{t}$ events. This figure is structured to achieve two main objectives: firstly, to analyze the correlation between each WP's efficiency and the variable η and p_T ; secondly, to clearly differentiate the efficiencies for muons that are directly produced versus those emerging from hadron decays.

4.3.4.3 Muon isolation

In the ATLAS experiment, stringent criteria are employed to ascertain the isolation of muons, which is vital for differentiating muons arising directly from prompt decays from those produced by hadronic processes or non-hard-scattering events. This involves evaluating both the transverse $|d_0|$ and longitudinal z_0 impact parameters of muon tracks, ensuring their proximity to the beam interaction point. The significance of these measurements, $|d_0|/\sigma(d_0)$ and $z_0\sin\theta$, must meet specific thresholds, with $|d_0|/\sigma(d_0)$ required to be less than 3. The d_0 is measured relative to the actual beam position and is defined in terms of its significance, whereas θ is the polar angle of muon tracks. The impact parameter resolutions of approximately $10\ \mu\text{m}$ and $50\ \mu\text{m}$ in the transverse and longitudinal planes respectively, for tracks with $p_T > 10\ \text{GeV}$.

The isolation criteria also include considering the surrounding environment of the muon, particularly focusing the energy deposits within the calorimeters and nearby charged particle

trajectory. The isolation is quantified by measuring the total energy and the scalar sum of the transverse momentum of tracks within a defined cone around the muon track. The sum should be below specific thresholds, which helps confirm the muon isolation from jet activity and its classification as a product of a prompt decay.

The primary isolation measurements include:

1. **Track-based isolation** p_T^{cone} involves the summation of p_T values of all tracks within a cone, defined by ΔR , around the muon, excluding the muon itself. This cone size adjusts either to 0.2 or to a dynamic value of $\min(0.2, 10 \text{ GeV}/p_T^{0.3})$ depending on muon's p_T .
2. **Calorimeter-based isolation** $E_T^{\text{topocone20}}$ measures the transverse energy within a cone of $\Delta R = 0.2$ around the muon, accounting for pile-up corrections and the muon's own contribution.
3. **Particle-flow-based isolation** blends track-based and calorimeter-based measurements using a weighting factor ($w = 0.4$) to optimize isolation, particularly effective against backgrounds involving heavy-flavour hadron decays.

Isolation WP	Definition	Track p_T requirements
PflowLoose*	$(p_T^{\text{varcone30}} + 0.4 \cdot E_T^{\text{neflow20}}) < 0.16 \cdot p_T^\mu$	$p_T > 500 \text{ MeV}$
PflowTight*	$(p_T^{\text{varcone30}} + 0.4 \cdot E_T^{\text{neflow20}}) < 0.045 \cdot p_T^\mu$	
Loose*	$p_T^{\text{varcone30}} < 0.15 \cdot p_T^\mu, E_T^{\text{topocone20}} < 0.3 \cdot p_T^\mu$	$p_T > 1 \text{ GeV}$
Tight*	$p_T^{\text{varcone30}} < 0.04 \cdot p_T^\mu, E_T^{\text{topocone20}} < 0.15 \cdot p_T^\mu$	
HighPtTrackOnly*	$p_T^{\text{cone20}} < 1.25 \text{ GeV}$	$p_T > 1 \text{ GeV}$
TightTrackOnly*	$p_T^{\text{varcone30}} < 0.06 \cdot p_T^\mu$	
PLBDTLoose (PLBDTTight)	$p_T^{\text{varcone30}} < \max(1.8 \text{ GeV}, 0.15 \cdot p_T^\mu)$ BDT cut to mimic TightTrackOnly (Tight) efficiency	$p_T > 1 \text{ GeV}$

Table 4–5 Definitions of the muon isolation WPs.

To accommodate different analysis requirements, multiple isolation working points (WPs) are defined in Table. 4–5. Each with specific performance criteria based on track isolation integrated with either calorimeter or particle-flow-based isolation. These WPs include:

- **Loose and Tight** WPs, which utilize a blend of track isolation and either calorimeter or neutral particle-flow isolation to balance muon detection efficiency with the robust

rejection of non-prompt muons.

- **High-Pt Track Only and Tight Track Only** WPs, which offer stringent isolation standards primarily using track isolation, ideal for environments with significant non-prompt muon backgrounds.
- **PLBDTLoose and PLBDTTight**, which employ a Boosted Decision Tree (BDT) based on a p_T -dependent threshold to mimic the efficiency levels of the most stringent track-only isolation WPs.

4.3.5 Jets

Jet reconstruction is an essential analytical method in particle physics, particularly at colliders. It involves the systematic examination of particle jets, which are cascades of particles originating from the high-energy collisions of protons, linked to the fundamental components of matter: quarks and gluons. This process utilizes sophisticated detection technologies, such as calorimeters and particle trackers, to precisely measure the energy and momentum of these jets. Advanced algorithms are employed to discern genuine jet signals from the confounding effects of pile-up proton-proton interactions. A subset of this field, b-jet reconstruction focuses on jets derived from bottom (b) quarks, which are pivotal for research into the Higgs boson and various significant physical phenomena. This involves the use of b-tagging techniques that exploit the unique decay signatures and displaced characteristics of b-hadrons to robustly identify and characterize b-jets.

4.3.5.1 Jet reconstruction using Particle flow algorithm

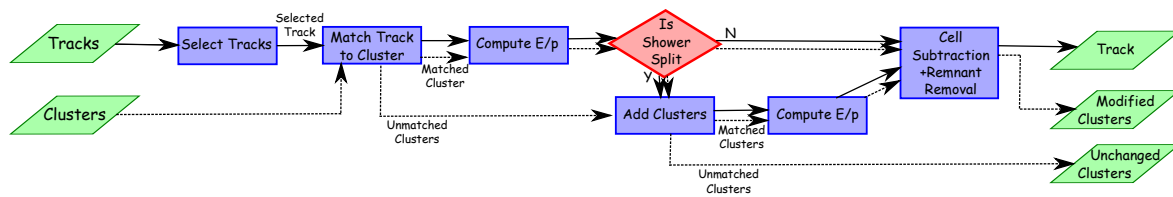


Figure 4–12 A flow chart illustrating the steps of the particle flow algorithm. The process begins with the selection of tracks and continues until the associated energy of these tracks is accounted for. The final output includes charged particles, topo-clusters that are unaltered by the algorithm, and remnants of topo-clusters where only partial energy has been removed.

Jet reconstruction at the ATLAS experiment at the LHC employs two primary methodologies: traditional calorimeter-based jet reconstruction and the more advanced particle flow

(Pflow) jet reconstruction. While the calorimeter-based approach groups topological clusters of calorimeter cells^[122] and applies a Jet Energy Scale (JES) correction factor for calibration^[123-124], it is limited in terms of resolution. On the other hand, the Pflow method^[125] integrates measurements from both the calorimeter and tracking systems, forming an ensemble of "particle flow objects". This integration significantly enhances the granularity and resolution, leading to more precise jet reconstruction.

The Pflow algorithm operates through a detailed, systematic procedure designed to optimize the reconstruction of hadronic jets and associated soft activity as shown in Fig. 4–12. The procedure begins by ordering particle tracks by descending transverse momentum (p_T) and matching them to corresponding topological clusters in the calorimeter. For each matched track-cluster pair, the algorithm calculates the expected energy deposition in the calorimeter based on the cluster's position and the track's momentum. It acknowledges that a single particle may deposit energy in multiple clusters and adjusts the system to encapsulate the full energy spread of the particle shower. Subsequently, the algorithm performs precise energy subtraction for these clusters to account for any overlap, followed by the removal of any residual energies that align with the expected fluctuations of a single particle's signal. This calibration process is essential for the accurate determination of the event's missing transverse momentum (E_T^{miss}), and the algorithm's robustness is validated against Monte Carlo simulations of single-pion and dijet events without pile-up.

Jet reconstructed using the Pflow method are focused using the anti- k_t algorithm^[126] with a radius parameter $R = 0.4$, focusing on clusters and tracks within $|\eta| < 2.2$ to minimize pile-up contributions. Furthermore, both Pflow and calorimeter jet reconstructions employ jet-ghost area^[127-128] subtraction to correct for pile-up, complemented by a numerical inversion to refine the overall jet response. The resultant Pflow jets, which consider both charged and neutral particles, exhibit a notably lower per-event energy density compared to their calorimeter-only counterparts, primarily due to a more effective exclusion of pile-up tracks.

JES corrections are adjusted to reflect variables such as the charged fraction and energy distributions across different calorimeter layers, ensuring a maximal fidelity in jet characteristics between data and MC simulations. Comparisons^[129] demonstrate a maximum deviation of less than 2% in jet characteristics, confirming the precision and reliability of the Pflow algorithm for comprehensive jet reconstruction in high-energy physics experiment.

4.3.5.2 b-jet identification

The identification of b-jets at the ATLAS detector involves a series of steps that help distinguish them from other types of jets^[130]:

- **Track Reconstruction** Tracks are formed in the Inner Detector and are considered for b-jet tagging if their transverse momentum (p_T) exceeds 500 MeV. This process boasts a high efficiency, usually capturing over 98% of relevant tracks in typical event scenarios, which is crucial for effectively identifying tracks originating from b-hadron decay. The high efficiency ensures accurate selection of b-hadrons which is important for analyses such as searches for rare decays and measurements of hadron properties.
- **Primary Vertex Reconstruction** The primary vertex for each event is determined by locating the area with the highest concentration of track momentum. This vertex serves as a critical reference for measuring the displacement of tracks and secondary vertices, crucial for identifying b-jets, which are characterized by the decay signatures of long-lived b-hadrons.
- **Jet Formation** Jets are constructed from clusters of energy in the calorimeter using the anti- k_t algorithm with a specified radius ($R = 0.4$). Adjustments are made to the jets' momenta to account for effects from pile-up and other sources to ensure accurate measurement.
- **Jet Vertex Tagger (JVT)** This tool discriminates between jets originating from the primary interaction and those from secondary pile-up events by evaluating the associated track and vertex information, helping to confirm the origin of jet.
- **Track-jet Matching** This involves matching tracks to jets based on their angular proximity, defined by ΔR , which helps in assessing the contribution of individual tracks to the overall jet structure.
- **Jet Labelling** Jet are labeled as b-jets if they include at least one b-hadron with $p_T \geq 5$ GeV within a defined proximity ($\Delta R = 0.3$) to the jet axis. If no hadrons are present, the presence of c-hadrons or τ leptons will classify the jets as c-jets or τ -jets, respectively.

These steps together provide a foundational method for identifying b-jets, which are essential for various physics including studies on the Higgs boson and top quark properties. However, in the ATLAS experiment, the full effectiveness of separating b-jets from other jets using traditional high-level b-tagging methods, such as MV2c10^[131-132], remains challenging. This

method employs the Boosted Decision Tree (BDT)^[133] in combination with kinematic features, but further enhancements are needed to improve separation accuracy.

To enhance the identification process, ATLAS also utilizes algorithms like IP3D, SV1, and JetFitter. These methods focus on calculating likelihoods based on the impact parameter significances S_{d0} and S_{z0} , processed in a product space of 29,400 bins. By assuming feature independence, these algorithms aim to capture critical interdependencies among the features, thereby providing a more robust framework for b-jet identification.

To overcome these limitations, Recurrent Neural Networks (RNNs)^[134-136] have been integrated due to their proficiency in handling sequences and capturing time-dependent correlations. An RNN processes a sequence of tracks $(x_1, x_2 \cdots x_n)$ through layers (h_t) dynamically updated by:

$$h_t = \phi(W_{hh}h_{t-1} + W_{xh}x_t + b_h). \quad (4-9)$$

where ϕ is a non-linear activation function, and W_{hh} , W_{xh} , and b_h are the weights and biases of the network. The final output, h_t , is a compressed representation of the jet's characteristics, which is then fed through a fully connected layer to produce a b-tagging discriminant.

The RNN approach enhances the b-tagging performance by leveraging its dynamic modeling capabilities to learn complex relationships within data sequences. This capability allows for significant improvements in b-tagging efficiency and background rejection compared to traditional methods, particularly across varying jet p_T values. The comprehensive discriminant used in the RNN-based b-tagging system is formulated as:

$$D_{\text{RNN}} = \ln\left(\frac{f_c \cdot P_c + f_r \cdot P_r + (1 - f_c - f_r) \cdot P_{\text{light}}}{P_b}\right) \quad (4-10)$$

where P_c , P_r (for residual jets), and P_{light} represent the conditional probabilities for c-jets, residual jets, and light jets respectively, derived from the RNN's output. The efficiencies f_c and f_r adjust the relative weighting of the probabilities in the discriminant formula, tuning the classifier's sensitivity to different jet flavours based on training data and desired tagging efficiency. By adopting RNNs, ATLAS benefits from a more sophisticated analysis framework that leverages the extended informational depth of sequential track data, leading to more precise and reliable b-jet identification.

The comparative performances of RNN and other algorithms are summarized in Fig. 4-13.

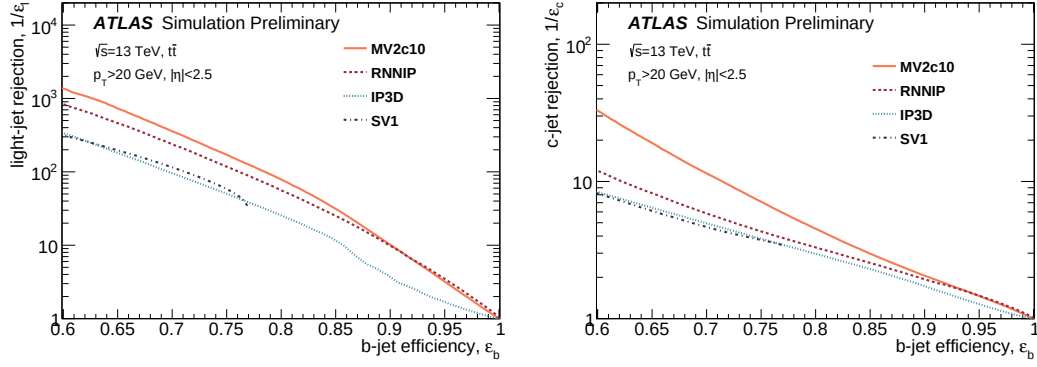


Figure 4–13 The diagrams compare the rejection rates of light-jets (left) and c-jets (right) versus the efficiency of b-tagging for jets with a transverse momentum (p_T) greater than 20 GeV and a pseudorapidity ($|\eta|$) less than 2.5. MV2c10, an advanced BDT tagger, combines IP3D output with additional vertex data from JetFitter and SV1. The statistical error in the data presented is less than 3%^[137].

4.3.6 Hadronic τ decays

The reconstruction of hadronically decaying tau ($\tau_{\text{had-vis}}$) candidates^[138] in high-energy physics, particularly within the ATLAS experiment, involves advanced methodologies for identifying and analyzing jets that potentially contain tau decay products. These jets are reconstructed using the anti- k_t algorithm with a distance parameter of $\Delta R = 0.4$ ^[126] and are required to have a transverse momentum (p_T) greater than 10 GeV and a pseudorapidity (η) within $|\eta| < 2.5$.

Vertex and Track Classification The identification of a candidate tau decay vertex within these jets relies on the highest p_T , weighted track fraction within an angular distance $\Delta R = 0.2$ ^[139] from the jet axis. This forms the basis for further classification using a set of Boosted Decision Tree (BDTs), which segment tracks within $\Delta R = 0.4$ into core and isolation tracks. These tracks undergo energy calibration adjustment involving pile-up subtraction and response correction focus within $\Delta R = 0.2$ ^[118,140] to accurately gauge the jet energy relating to the tau candidate.

RNN Enhancement for tau Identification Enhancing the discrimination power against jet mimicking tau signatures, the Recurrent Neural Network (RNN) model integrates both low-level and high-level variables^[141]. Low-level variables include $p_{\text{track}T}$, $d_{\text{track}0}$, $z_{\text{track}0}\sin\theta$, $\Delta\eta_{\text{track}}$

and the number of hits across various detector layers. High-level variables comprise $p_{\text{seed jetT}}$, f_{cent} , $f_{\text{lead track}}^{-1}$, ΔR_{max} , $|S_{\text{lead track}}|$, S_{flightT} , f_{trackiso} , f_{EMtrack} , and $m_{\text{EM+track}}$. These variables help refine the identification process, effectively categorizing tau decays into one-prong and three prong configurations.

Performance Metric and Rejection Power The effectiveness of the RNN-based identification approach, particularly in contrast to traditional BDT methods, is quantified through performance metrics that showcase its superior rejection power. The RNN model demonstrates significantly higher efficacy in discriminating true $\tau_{\text{had-vis}}$ ^[139] decays from backgrounds across various prong configurations, as evidenced by comparative rejection power curves as illustrated in Fig. 4–14. The algorithm defines working points labeled as VeryLoose, Loose, Medium, and Tight, with each threshold enhancing the specificity and selectivity of the tau identification process.

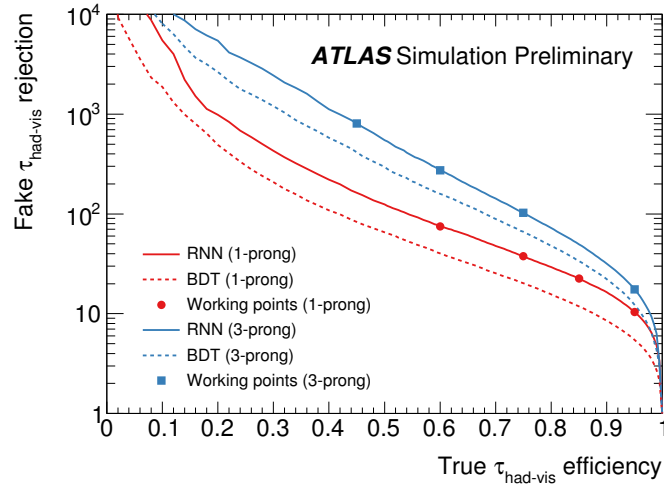


Figure 4–14 The graph depicts the rejection rates for quark and gluon jets that are incorrectly identified as one-prong (represented in red) and three-prong (depicted in blue) hadronic tau ($\tau_{\text{had-vis}}$) candidates. These rates are evaluated for both RNN-based (solid line) and BDT-based (dashed line) identification algorithms across four designated working points: Tight, Medium, Loose, and VeryLoose, each corresponding to increasing levels of signal selections stringency^[142].

4.3.7 Missing transverse energies

The reconstruction of missing transverse energy (MET)^[143], denoted as E_T^{miss} , in the ATLAS experiment is quantified from two principal sources:

- **Hard-event signals** These include calibrated particles such as electrons, photons, tau leptons, muons, and jets.
- **Soft-event signals** This component is derived from tracks not associated with hard objects but linked to the primary vertex.

The overall MET is calculated as following:

$$E_{x(y)}^{\text{miss}} = - \sum_{i \in (\text{hard objects})} p_{x(y),i} - \sum_{j \in (\text{soft signals})} P_{x(y),j} \quad (4-11a)$$

$$\vec{E}_T^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}) \quad (4-11b)$$

$$E_T^{\text{miss}} = |\vec{E}_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (4-11c)$$

$$\phi^{\text{miss}} = \tan^{-1}(E_y^{\text{miss}}/E_x^{\text{miss}}) \quad (4-11d)$$

The comprehensive formula for missing transverse momentum, E_T^{miss} , is expressed as:

$$\vec{E}_T^{\text{miss}} = - \left(\underbrace{\sum_{\text{selected electrons}} \vec{p}_T^e}_{\vec{E}_T^{\text{miss},e}} + \underbrace{\sum_{\text{accepted photons}} \vec{p}_T^\gamma}_{\vec{E}_T^{\text{miss},\gamma}} + \underbrace{\sum_{\text{accepted } \tau\text{-leptons}} \vec{p}_T^{\tau_{\text{had}}}}_{\vec{E}_T^{\text{miss},\tau_{\text{had}}}} + \underbrace{\sum_{\text{selected muons}} \vec{p}_T^\mu}_{\vec{E}_T^{\text{miss},\mu}} + \underbrace{\sum_{\text{accepted jets}} \vec{p}_T^{\text{jet}}}_{\vec{E}_T^{\text{miss},\text{jet}}} + \underbrace{\sum_{\text{unused tracks}} \vec{p}_T^{\text{track}}}_{\vec{E}_T^{\text{miss},\text{track}}} \right). \quad (4-12)$$

hard term
soft term

This is broken down into individual contributions from selected electrons, accepted photons, accepted tau leptons, selected muons, accepted jets, and unused tracks, respectively represented as $E_{T,\text{miss},e}$, $E_T^{\text{miss},\gamma}$, $E_T^{\text{miss},\tau}$, $E_T^{\text{miss},\mu}$, $E_T^{\text{miss},\text{jet}}$, and $E_T^{\text{miss},\text{track}}$.

Chapter 5 Precise Measurement of Differential Cross-sections for $Z\gamma$ +jets

5.1 Introduction

Precision measurements of $Z\gamma$ ^[144-148] production at the LHC are pivotal for advancing our understanding of the SM and probing potential new physics beyond the SM. These measurements, especially in the absence of direct evidence of new physics, are essential for constraining the parameters within the SM Lagrangian. Central to this study is the examination of color singlet production in association with Quantum Chromodynamics (QCD) radiation^[149], where the sensitivity to hadronic activity through kinematic recoil offers insights into the strong coupling constants and masses. The kinematic distributions derived from these events are instrumental in fitting SM parameters and calibrating models used across various hadron collider observables, including Parton Distribution Functions (PDFs) and predictions incorporating resummation of Sudakov logarithms^[150]. Accurate predictions of differential distributions are crucial for identifying any small deviations that could signal new physics.

The primary goal of this research is to measure the differential cross-section for jet variables in $Z\gamma$ production. Jet activity, which can significantly alter the shape of Born-level observables, is crucial for QCD studies and can aid in distinguishing between SM and BSM physics. This process, particularly when the Z boson decays into charged leptons, is valuable due to its fully reconstructable final state. The relative large cross-section and small background contribution, making it an excellent candidate for testing both the SM and BSM physics. Anomalous gauge couplings, such as $ZZ\gamma$ and $\gamma Z\gamma$, which are absent in the SM, can be investigated through these precise measurements. The identification of such couplings would manifest as deviations in the kinematic distributions of $Z\gamma$ events, notably in the tails of transverse momentum (p_T) distributions^[151].

The analysis also distinguishes between Initial State Radiation (ISR) and Final State Radiation (FSR) by evaluating the invariant mass distributions. Additionally, polarization studies of the Z boson provide further verification of SM predictions and explore BSM effects. These studies have been conducted previously, but the existence of an ISR photon introduces new

effects affecting the angular distribution of final state particles.

Fig. 5–1 illustrates the various $Z\gamma$ productions.

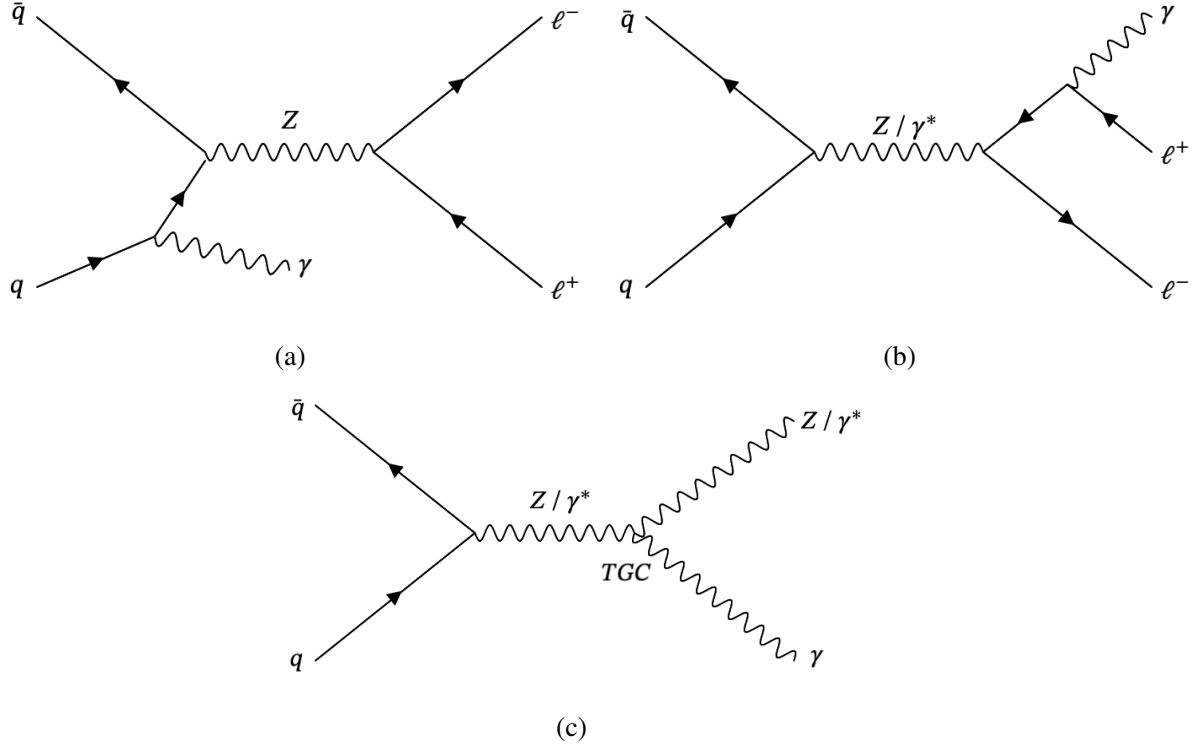


Figure 5–1 Diagrams illustrating $Z\gamma$ production through the ISR process (a), FSR process (b), and an example of anomalous triple gauge couplings (aTGC)(c)^[148].

5.2 Data and Monte Carlo samples

5.2.1 Data and Analysis Framework

This analysis uses data recorded by the ATLAS detector^[47] from proton-proton (pp) collisions at the LHC during Run 2, which covers the period from 2015 to 2018. Events are chosen based on the lowest unscaled single lepton triggers, as outlined in Table. 5–1.

These events must also meet general cleaning criteria, including passing the Good Run List (GRL) requirements^[152]. The GRLs used in this analysis are summarized in Table 5–2.

The total integrated luminosity used for this analysis amounts to 139 fb^{-1} , recorded annually as follows:

- 2015: 3219.6 pb^{-1} (OfLumi-13TeV-009)

Trigger Type	2015 data taking	2016 - 2018 data taking
Single electron	HLT_e24_lhmedium_L1EM20VH	HLT_e26_lhtight_nod0_ivarloose
	HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
	HLT_e120_lhloose	HLT_e140_lhloose_nod0
Di-electron	HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0
		HLT_2e24_lhvloose_nod0
Single muon	HLT_mu20_iloose_L1MU15	HLT_mu26_ivarmedium
	HLT_mu50	HLT_mu50
Di-muon	HLT_mu18_mu8noL1	HLT_mu22_mu8noL1

Table 5–1 Lepton triggers employed in this analysis at 13 TeV.

Year	GRL XML File
2015	data15_13TeV.periodAllYear_DetStatus-v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns.xml
2016	data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml
2017	data17_13TeV.periodAllYear_DetStatus-v99-pro22-01_Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim.xml
2018	data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim.xml

Table 5–2 The Good Run Lists by years.

- 2016: 32988.1 pb⁻¹ (OfLumi-13TeV-010)
- 2017: 44307.4 pb⁻¹ (OfLumi-13TeV-010)
- 2018: 58450.1 pb⁻¹ (OfLumi-13TeV-010)

The analytical process utilizes data initially formatted in xAOD, which is subsequently transformed into DxAOD using the HIGG1D2 derivation framework. This transformation, realized by HGamGamStar^[153] framework, is optimised from the analysis to accommodate signal events featuring lepton plus photon final states.

5.2.2 Monte Carlo Simulations

The simulation framework for this analysis utilizes three distinct Monte Carlo (MC) campaigns: mc16a, mc16d, and mc16e. These campaigns replicate the conditions of the LHC runs for 2015-2016, 2017, and 2018, respectively, with a focus on the interaction multiplicity per bunch crossing. By tailoring each campaign to specific periods, the framework ensures that simulations closely match the actual experimental conditions.

To align the simulated events with real collision data, a reweighting strategy is applied using the PileupRewightingTool^[154]. This tool adjusts the simulations to account for variations

in pileup, which involves multiple overlapping collisions within the same event. Harmonizing simulated events with actual data enhances the accuracy and reliability of the analysis. The event samples generated from these simulations are subsequently scaled according to their theoretical cross-sections, ensuring the consistency with expected physical processes.

5.2.2.1 Monte Carlo samples

Building on this robust simulation framework, four distinct samples are used to model the $Z\gamma$ process, each generated using different configurations and frameworks to provide comprehensive coverage and precision.

The nominal sample is produced using SHERPA 2.2.11. This sample includes the matrix element with up to one additional parton at next-to-leading order (NLO) and up to four additional partons at leading order (LO). The parton shower is modelled using MEPS@NLO with the NNPDF30nnlo PDF set, and Frixione isolation parameter set to $\delta_0 = 0.1$, $\epsilon = 0.1$ and $\eta = 2$. This sample requires a photon p_T threshold of $p_T^\gamma > 15$ GeV. A second sample is generated with SHERPA 2.2.4 at leading order with up to four additional partons, using the same parton shower and isolation parameters as the nominal sample. This sample is sliced in photon transverse momentum p_T to enhance statistics at high p_T region, with a lower p_T^γ threshold of 7 GeV.

The third sample employs SHERPA 2.2.8, incorporating up to one additional parton at NLO and up to three additional partons at LO. Merging is performed using MEPS@NLO with NNPDF30nnlo PDF set, with a photon p_T^γ threshold of 7 GeV, similar to SHERPA 2.2.4 sample. The fourth sample is generated using MADGRAPH5_AMC@NLO 2.3.3, which includes up to one extra parton at NLO in the matrix element with NNPDF30_nlo_as_0118 PDF set. This sample follows the same isolation criteria as the SHERPA samples. All MC samples are summarized in Table 5–3.

This analysis aims to deliver precise and comprehensive measurements of $Z\gamma$ process by integrating these detailed samples within the simulation framework, facilitating testing of the SM and exploring potential new physics.

Process	Generator	Parton shower	PDF	Tune
$Z\gamma$ 0,1,2,3 j @LO	SHERPA 2.2.4	SHERPA	NNPDF30 NNLO	SHERPA default
$Z\gamma$ 0,1 j @NLO + 2,3 j @LO	SHERPA 2.2.8	SHERPA	NNPDF30 NNLO	SHERPA default
$Z\gamma$ 0,1 j @NLO + 2,3,4 j @ LO	SHERPA 2.2.11	SHERPA	NNPDF30 NNLO	SHERPA default
$Z\gamma$ 0.1 j @NLO	MADGRAPH	PYTHIA8	NNPDF30 NLO	A14
Z +jets 0 j @NLO	POWHEGBox	PYTHIA8	CTEQ6L1	AZNLO
$t\bar{t}\gamma$	MADGRAPH5_aMc@NLO	PYTHIA8	NNPDF23 LO	A14
$tW\gamma$ @LO	MADGRAPH5_aMc@NLO	PYTHIA8	NNPDF23 LO	A14
$ZZ \rightarrow \ell\ell\ell\ell$	SHERPA 2.2.2	SHERPA	NNPDF30 LO	SHERPA default
$W^\pm Z \rightarrow \ell\ell\nu$	SHERPA 2.2.2	SHERPA	NNPDF30 LO	SHERPA default
0,1 j @NLO + 2,3 j @LO				
$WZ\gamma$ 0j @NLO + 1,2 j @LO	SHERPA 2.2.11	SHERPA	NNPDF30 NNLO	SHERPA default
$WW\gamma$ 0j @NLO + 1,2 j @LO	SHERPA 2.2.11	SHERPA	NNPDF30 NNLO	SHERPA default

Table 5–3 Summarized Monte Carlo samples used in this analysis.

5.3 Analysis Methodology

The measurement of the $Z\gamma$ differential cross-section is conducted within a defined kinematic phase space. This analysis targets event featuring a Z boson and a photon, requiring two Opposite Sign Same Flavor (OSSF) leptons (electrons or muons) to reconstruct Z boson, and at least one signal photon. Events must meet specific kinematic criteria, such as transverse momentum and invariant mass threshold, to effectively isolate the signal and minimize background interference.

The analysis pileline consists of several key stages:

- **Pre-selections** Initial filtering of events based on a set of baseline criteria.
- **Background Modelling** Definition of control region to estimate background contributions and to validate the methodology.
- **Statistical Analysis** Assessing systematic uncertainties to ensure the robustness and reliability of the measurement.
- **Differential Measurements** Performing differential cross-section measurements to analyze the distribution of events as functions of various kinematic variables.

5.3.1 Object definitions

To ensure accurate event reconstruction and analysis, precise object definitions are crucial. Object definitions employ the recommendations^[155] from the CP groups and are applied within the HGamGamStar^[153] framework.

Objects are divided into baseline and signal categories to achieve precise event selection. Pre-selection variables include transverse momentum (p_T), pseudorapidity (η), and impact parameter criteria introduced in Section. 3.2. Detailed definitions are summarized in the Table. 5–4.

Objects	Property	requirements
Electrons	Kinematics	$p_T > 25 \text{ GeV} \ \& \ \eta < 2.47$, (excl. $1.37 < \eta < 1.52$)
	Identification	Medium
	Isolation	FCLoose
	Impact parameter	$ d_0/\sigma(d_0) < 5$, $ z_0\sin\theta < 0.5$
Muons	Kinematics	$p_T > 25 \text{ GeV} \ \& \ \eta < 2.5$
	Identification	Medium
	Isolation	PflowLoose_FixedRadIso
	Impact parameter	$ d_0/\sigma(d_0) < 3$, $ z_0\sin\theta < 0.5$
Photons	Baseline	
	Kinematics	$p_T > 15 \text{ GeV} \ \& \ \eta < 2.37$, (excl. $1.37 < \eta < 1.52$)
	Identification	Loose
	Signal	
Jets	Kinematics	$p_T > 30 \text{ GeV} \ \& \ \eta < 2.37$, (excl. $1.37 < \eta < 1.52$)
	Identification	Tight
	Isolation	FixedCutLoose
	Algorithm	anti- k_t ($R=0.4$, PFlow)
Jets	Kinematics (baseline)	$p_T > 25 \text{ GeV} \ \& \ \eta < 4.4$
	Kinematics (signal)	$p_T > 30 \text{ GeV}$ if $ \eta < 2.5$ $p_T > 50 \text{ GeV}$ if $2.5 < \eta < 4.4$
	Pileup Mitigation ^[156-157]	JVT Medium for $p_T > 120 \text{ GeV} \ \& \ \eta < 2.5$

Table 5–4 Summarized object definitions utilized in this analysis, including details on both baseline and signal definitions.

To prevent ambiguities where an object might simultaneously fit into multiple categories and to ensure precise classification, an Overlap Removal (OR)^[158] procedure is implemented for baseline objects. This process enhances the clarity and accuracy of event reconstruction by uniquely categorizing each object. The OR procedure is applied sequentially as follows:

- **Jets:** Removed if within $\Delta R < 0.4$ of a photon, or within $\Delta R < 0.2$ of an electrons
- **Electrons and Muons:** Removed if within $\Delta R < 0.4$ of a jet
- **Photons:** Removed if within $\Delta R < 0.4$ of an electron or muon

- **Electrons:** Finally removed if within $\Delta R < 0.2$ of a muon

5.3.2 Event Selections

The differential cross-section of $Z\gamma$ production is measured within a specific Signal Region (SR) designed to ensure precise signal isolation. Initially, events must meet lepton trigger requirements as outlined in Table. 5–1. Subsequently, two Opposite Sign Same Flavor (OSSF) leptons are selected. Transverse momentum (p_T) threshold are imposed on both leptons and photons to ensure that the selected objects are prompt and well-defined. To further refine the event selection, the invariant mass of the lepton pair (m_{ll}) must exceed 40 GeV to avoid contributions from low-mass resonances. Additionally, to exclude Final State Radiation (FSR) events, the combined invariant mass of the dilepton and photon system must be greater than 182 GeV ($m_{ll} + m_{ll\gamma} > 182$ GeV). This comprehensive set of criteria ensures high precision in the measurement of the $Z\gamma$ differential cross-sections.

A Control Region (CR) is defined to validate the modelling of the $t\bar{t}\gamma$ background. This is achieved by selecting events where the leptons have Opposite Sign Different Flavors (OSDF) but still adhere to the same signal selection criteria. In this control region, the characteristic signature is $e\mu\gamma$, with at least one photon having $p_T > 30$ GeV. All other requirements of the signal region are also applied to the Control Region to maintain consistency. A comprehensive summary of these selection criteria is provided in Table. 5–5.

Analysis Requirements	
Variable	Selection
N_l	≥ 2 signal leptons (OSSF for SR, OSDF for CR)
Trigger	lepton triggers
Leading lepton	$p_T > 30$ GeV
Photon	≥ 1 signal photon with $p_T > 30$ GeV
m_{ll}	> 40 GeV
$m_{ll} + m_{ll\gamma}$	> 182 GeV

Table 5–5 Summarized event selections applied in this analysis.

5.3.3 Variables

The objective of this work is to measure the differential cross-section of $Z\gamma$ + jets events, and this section defines the variables measured in this analysis. The variables are categorized into two types: 1D and 2D.

5.3.3.1 1D variables

This work considered several 1D variables, which are crucial for QCD studies, listed as follows:

1. **Benchmark variables** from previous analyses for comparison
 - p_T^γ : Photon transverse momentum
 - p_T^Z : Transverse momentum of the Z boson
 - $m_{ll\gamma}$: Invariant mass of the lepton-photon system
2. **Variables sensitive to additional QCD radiations** useful for comparing parton shower (PS) results with analytical resummation
 - N_{jet} : Number of selected jets
 - p_T^{jet1} and p_T^{jet2} : Transverse momentum of the leading and subleading jets
 - $p_T^{\text{jet2}}/p_T^{\text{jet1}}$: Ratio of the transverse momentum of the two leading jets
 - $m_{ll\gamma j}$: Invariant mass of the lepton-photon-jet system
 - m_{jj} : Invariant mass of the di-jet system
3. **Variables from Dark Matter Searches** help to constrain Zh to invisible decays, where the Higgs boson is produced with a Z boson but decays into invisible particles
 - H_T : Scalar sum of the p_T of all jets, leptons, and photons
 - $p_T^\gamma/\sqrt{H_T}$: Ratio of the transverse momentum of the lepton to the square root of H_T
 - $\Delta\phi(j, \gamma)$: Azimuthal difference between the leading jet and leading photon
 - $\Delta R(\ell, \ell)$: Distance in the $\eta - \phi$ plane between the two leptons

5.3.3.2 2D variables

In addition to 1D distributions, a 2D analysis is conducted to enhance sensitivity by considering pairs of variables. Theoretical predictions for $Z\gamma$ events at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) provide precise differential distributions. Calculations are dominated by Sudakov logarithms^[150] due to soft and collinear emissions

especially in regions where the transverse momentum (q_T) is much smaller than the mass of the color singlet (Q)^[159-160]. These terms are treated with resummation, giving precise predictions at next-to-leading-logarithm (NLL)^[161] and next-to-next-to-leading-logarithm (NNLL)^[162] accuracy.

The 2D measurements focus on combinations of "hard variables" and "resolution variables". "Hard variables" represent the hard scale of the processes and are non-zero at leading order (LO), such as p_T^Z , p_T^γ , and $m_{Z\gamma}$. "Resolution variables" are sensitive to additional QCD radiation and are zero at LO, increasing with higher QCD activity, such as $p_T^{Z\gamma}$ or N_{jet} . The 2D planes measured are:

1. $(p_T^Z/m_{Z\gamma}, m_{Z\gamma})$, $p_T^Z/m_{Z\gamma}$ is a resolution variable and $m_{Z\gamma}$ is a hard variable. Three bins of $m_{Z\gamma}$ are defined to study the evolution with the hard process: $150 \text{ GeV} < m_{Z\gamma} < 200 \text{ GeV}$, $200 \text{ GeV} < m_{Z\gamma} < 300 \text{ GeV}$, and $m_{Z\gamma} > 300 \text{ GeV}$. A lower cut of 125 GeV is applied to remove events with low mass resonance.
2. $(p_T^Z - p_T^\gamma, p_T^Z + p_T^\gamma)$, analyzing the diagonal region is significant for resummation calculations. To address this, the scalar difference $p_T^Z - p_T^\gamma$ and scalar sum $p_T^Z + p_T^\gamma$ are employed. These variables are linear combination of p_T^Z and p_T^γ , where $p_T^Z - p_T^\gamma$ functions as a resolution variable but $p_T^Z + p_T^\gamma$ serves as a hard variable. Three bins of $p_T^Z + p_T^\gamma$ are defined: $p_T^Z + p_T^\gamma < 200 \text{ GeV}$, $200 \text{ GeV} < p_T^Z + p_T^\gamma < 300 \text{ GeV}$, and $p_T^Z + p_T^\gamma > 300 \text{ GeV}$.
3. $(p_T^{Z\gamma}, p_T^{Z\gamma\text{jet}})$, this set of variables helps to understand additional jet emission relative to the $Z\gamma$ system, and $p_T^{Z\gamma\text{jet}}$ is measured in bins of $p_T^{Z\gamma}$: $p_T^{Z\gamma} < 50 \text{ GeV}$, $50 \text{ GeV} < p_T^{Z\gamma} < 75 \text{ GeV}$, and $p_T^{Z\gamma} > 75 \text{ GeV}$.

Additionally, all variables used in 2D measurements are measured inclusively on their respective variables, including $p_T^{Z\gamma}$, $p_T^{Z\gamma\text{jet}}$, $p_T^Z - p_T^\gamma$, $p_T^Z + p_T^\gamma$, $p_T^Z/m_{Z\gamma}$, and $m_{Z\gamma}$.

5.3.3.3 Polarization variables

Understanding the polarization state of the Z boson is essential for probing the underlying dynamics of its production and decay mechanism. Polarization provides insights into the spin alignment and interactions of the Z boson with other particles, influenced by both electroweak and QCD processes. Analyzing polarization in $Z\gamma$ events, helps test the electroweak sector of the SM and search for potential new physics effects. The presence of an initial-state radiation (ISR) photon can modify the transverse momentum of the Z boson, making the study of its

polarization in $Z\gamma$ events distinct from that in $Z + \text{jets}$ events.

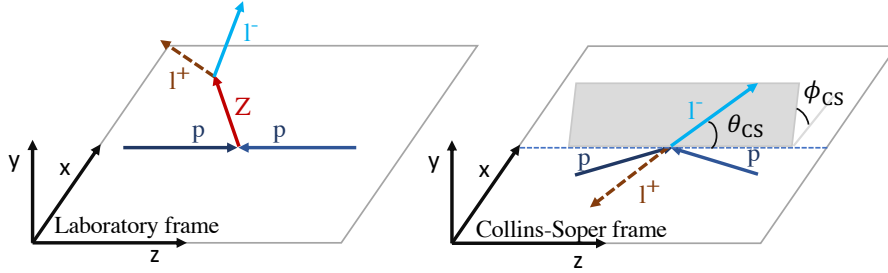


Figure 5–2 Comparison between the Laboratory Frame (left) and the Collins-Soper frame (right).

The polarization state of the Z boson is determined by analyzing the angular distribution of the negatively charged lepton (electron or muon) from the Z boson decay in the Z-boson rest frame. The Collins-Soper (CS) reference frame^[163] is employed in this analysis to define the rest frame axes, as illustrated in Fig. 5–2. This frame is defined by a plane spanned by the directions of the incoming protons. Key angular variables include $\cos \theta$ (θ is the polar angle) and ϕ (azimuthal angle), defined by the lepton in the Collins-Soper frame. These variables depend on the transverse momentum (p_T^Z) and rapidity of the Z boson.

In this analysis, we employ 2D unfolding techniques to correct for detector effects of the Z boson properties as function of p_T^Z . The 2D unfolding is performed by transforming two-dimensional histograms into one-dimensional histograms. There are 5 bins for p_T^Z and 8 bins for the differential variables ($\cos \theta_{CS}$, ϕ_{CS}). Thus, the one-dimensional histogram is structured into 5×8 bins where the second dimension of the two-dimensional histogram is wapped as several consecutive sub-ranges of the first dimension as shown in Fig. 5–3.

5.3.4 Background Estimation

Background events are critical as they can resemble the signal and complicate the extraction of meaningful data. Precise estimation and mitigation of these backgrounds are essential for the integrity of the measurements.

cation based on shower shape variables. These variables define a two-dimensional plane illustrated in Fig. 5–4.

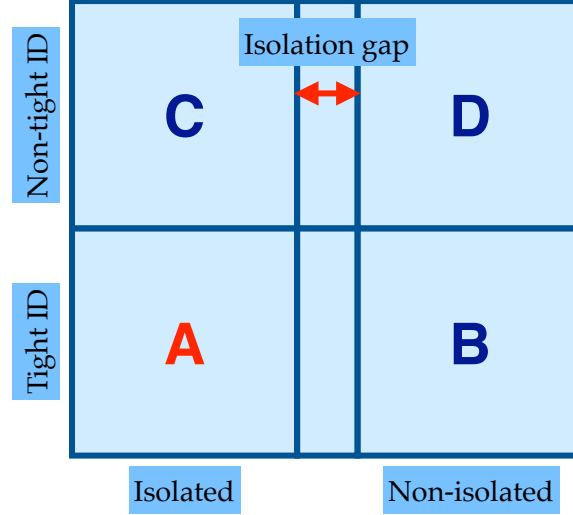


Figure 5–4 Illustration of the different regions used in the two-dimensional sideband method for Z +jets background estimation.

Events are divided into four regions based on isolation and tight identification selections:

- **Region A (Signal Region)** The photon satisfies both the tight identification and isolation criteria ($E_T^{\text{iso}} < 0.065p_T^\gamma$).
- **Region B** The photon meets the tight identification criteria but fails the isolation criteria ($E_T^{\text{iso}} > 0.065p_T^\gamma + E_{\text{gap}}$).
- **Region C** The photon fails the tight identification criteria (passes LoosePrime4) but fulfills the isolation criteria ($E_T^{\text{iso}} < 0.065p_T^\gamma$).
- **Region D** The photon does not satisfy either the tight identification (passes LoosePrime4) or the isolation criteria ($E_T^{\text{iso}} > 0.065p_T^\gamma + E_{\text{gap}}$).

Photon candidates that do not satisfy the tight identification criteria are required to pass the LoosePrime4 identification (anti-tight ID). This identification criteria is achieved by omitting four ECAL shower shape variables from the Loose ID identification^[155]. The isolation gap (E_{gap}) is set to 2 GeV.

Estimation strategy The estimation procedure comprises three main stage: determination of correlation factor R , calculation of purity P , and estimation for number of Z +jets events.

Each of these steps incorporates specific parameters and calculations to ensure accurate estimation of Z+jets background.

1. **Define the correlation factor** The correlation factor R accounts for correlations between different regions.

$$R = \frac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}} \quad (5-1)$$

where N_X^{Z+jets} represents the number of Z+jets events in region X ($X = A, B, C, D$) derived from MC simulations. R should be equal to 1 if the four regions are uncorrelated. However, a measured correlation factor is $R = 1.30 \pm 0.04(\text{stat})$ for LoosePrime4 anti-tight ID and $E_{\text{gap}} = 2$ GeV.

2. **Define the signal leakage parameters** Signal leakage into different regions is quantified using the signal leakage parameters:

$$c_B = \frac{N_B^{\text{sig}}}{N_A^{\text{sig}}}, c_C = \frac{N_C^{\text{sig}}}{N_A^{\text{sig}}}, c_D = \frac{N_D^{\text{sig}}}{N_A^{\text{sig}}} \quad (5-2)$$

where N_X^{sig} is the number of $Z\gamma$ signal events in region X ($X = A, B, C, D$) obtained from the $Z\gamma$ MC simulation.

3. **Calculate the purity P** Purity P is defined as the ratio of signal $Z\gamma$ events to the total number of $Z\gamma$ and Z+jets events.

$$P = \frac{N_A^{\text{sig}}}{N_A^{\text{data}} - N_A^{\text{bkg}}} \quad (5-3)$$

where the number of signal events in the signal region is calculated as $N_A^{\text{sig}} = N_A^{\text{data}} - N_A^{\text{bkg}} - N_A^{Z+jets}$.

4. **Determine the number of Z+jets events** The Z+jets background in the signal region is given by:

$$N_A^{Z+jets} = (N_A^{\text{data}} - N_A^{\text{bkg}}) \times (1 - P) \quad (5-4)$$

The parameters utilized in the ABCD method are detailed in Table 5–6.

Additionally, Table 5–7 presents the results of Z+jets estimation.

Although the uncertainties in the Z+jets estimates are relatively high, the impact on the total estimate (background + signal) remains low due to the small fraction of Z+jets, which is approximately 10%. The systematic uncertainty in Z+jets background will be discussed in the Systematic section.

Anti-tight	LoosePrime4
Isolation gap	2 GeV
R	$1.30 \pm 0.04(\text{stat.}) \pm 0.23(\text{syst.})$
$c_B (\times 10^{-3})$	$13.4 \pm 0.1(\text{stat.}) \pm 2.1(\text{syst.})$
$c_C (\times 10^{-3})$	$56.1 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.})$
$c_D (\times 10^{-3})$	$1.9 \pm 0.0(\text{stat.}) \pm 0.2(\text{syst.})$
$N_A^{\text{data}} - N_A^{\text{bkg}}$	$91704 \pm 311(\text{stat.}) \pm 566(\text{syst.})$
$N_B^{\text{data}} - N_B^{\text{bkg}}$	$3554 \pm 60(\text{stat.}) \pm 9(\text{syst.})$
$N_C^{\text{data}} - N_C^{\text{bkg}}$	$15853 \pm 127(\text{stat.}) \pm 31(\text{syst.})$
$N_D^{\text{data}} - N_D^{\text{bkg}}$	$3825 \pm 62(\text{stat.}) \pm 2(\text{syst.})$

Table 5–6 Summary of parameters used in the ABCD method for the entire phase-space. The systematic uncertainties for the correlation factor arise from variables in the isolation gap and anti-tight identification criteria. The signal leakage parameters are varied by changing the generators. The details of systematic uncertainties for Z+jets background estimation will be discussed in the next section.

Source	ee ($N^{Z+\text{jets}} = 4002.6$)	$\mu\mu$ ($N^{Z+\text{jets}} = 5884.8$)	$ee + \mu\mu$ ($N^{Z+\text{jets}} = 9773.0$)
Statistical	6.9%	6.9%	4.8%
Background	5.8%	5.0%	3.9%
Generator	10.1%	8.7%	8.6%
E_{gap}	7.6%	8.5%	7.0%
Anti-tight	19.9%	20.6%	19.8%
Total uncertainties	22.6%	23.7%	22.4%

Table 5–7 Summary of systematic uncertainties [in percentage] and their impact on the Z+jets estimates.

5.3.4.2 Pile-up photon background estimation

The estimation of the pile-up photon background involves a multi-step process to accurately evaluate the fraction of pile-up (PU) events (f_{PU}) within the data. This background arises from photon and Z boson produced in different proton-proton collisions occurring within the same bunch crossing. To achieve better resolution in $\sigma(z)$, only photons^[166] that converted in the Inner Detector (ID) are considered. The f_{PU} for converted photon is assumed to be the same as the unconverted photons, since the probability of having a pile-up photon to depend on the conversion inside the ID is not expected. The fraction f_{PU} is determined by

comparing the number of pile-up events (N_{PU}) to the total number of events ($N_{\text{Total Data}}$), and expressed as:

$$f_{\text{PU}} = \frac{N_{\text{PU}}}{N_{\text{Total Data}}} = \frac{N_{\text{PU, pixel conv}}}{N_{\text{Data, pixel conv}}} \quad (5-5)$$

and estimated to be $f_{\text{PU}} = 0.02 \pm 0.03(\text{stat.})$.

The methodology relies on evaluating the longitudinal separation (Δz) between the reconstructed primary vertex (z_{vtx}) and the photon position (z_γ). For real $Z\gamma$ events, Δz tends to be close to zero, while for pile-up events, the Δz distribution is broader. This is modelled using a Gaussian distribution for the primary vertex position z_{vtx} with a width of $\sigma(z_{\text{vtx}}) \approx 35$ mm, as shown in Fig. 5–5. The spread of the beam is similarly represented as $\sigma(z_\gamma)$, resulting in a combined Gaussian distribution with a width of $\sigma \approx 50$ mm.

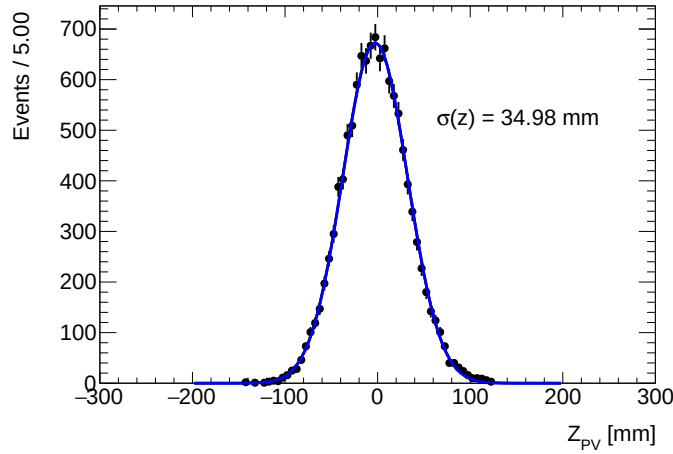


Figure 5–5 Distribution of primary vertex z positions in data. The blue line represents the fit to the data.

To extract the number of pile-up events (N_{PU}), the longitudinal separation of the photon conversion (Δz) is used, specifically from pixel conversions. This measurement is compared against the expected primary vertex distribution to distinguish between pile-up and $Z\gamma$ events, particularly in the tails of the Δz distribution illustrated in Fig. 5–6. The accuracy of the pile-up photon background estimation is further validated by comparing with Monte Carlo (MC) simulations and applying necessary corrections based on observed data distributions. The number of pile-up background events can be extracted as:

$$N_{\text{PU, pixel conv}} = N_{\text{Data, pixel conv}} - N_{\text{single pp, pixel conv}} \quad (5-6)$$

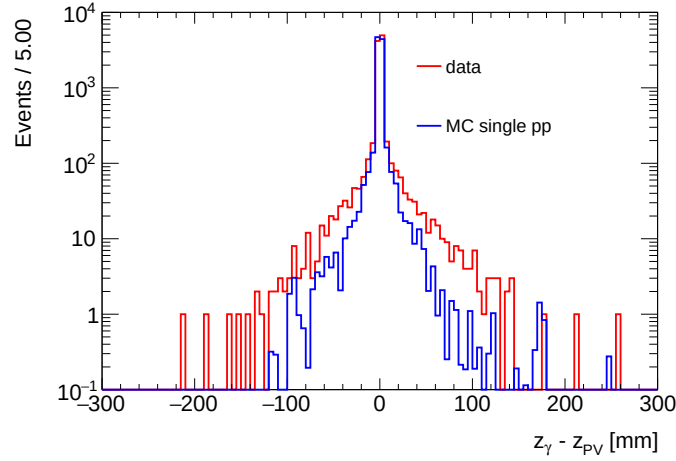


Figure 5–6 Distribution of Δz for both data with converted photons (red) and $Z\gamma$ MC events (blue).

This estimation procedure incorporates a robust validation and correction process by comparing truth samples with pile-up enhanced samples. This approach ensures systematic uncertainties are properly accounted for, especially for distributions that involve jet variables. In pile-up events where the photon is normally produced back to back with a jet, therefore a peak at $N_{\text{jet}} = 1$ is expected. However, Jet Vertex Tagger (JVT) reduces misidentification and migrates the peak to zero. The probability of events with misidentified jets is effectively decreased as the increase of the separation between the photon and the primary vertex by plotting the fraction of events with at least one jet as a function of Δz . Jets from the recoil of the photon are more likely to be removed by JVT when the photon is further away from the primary vertex, as shown in Fig. 5–7.

Two samples are used to estimate systematic uncertainties for pile-up background:

Truth sample A combination of MC Z +jets events with a single photon sample, scaled by a reconstruction efficiency obtained from the Z +jets sample. This process is designed to simulate the effects of the JVT cut applied during the reconstruction, which eliminates jets that do not originate from the primary vertex, which in PU events correspond to the highest p_T vertex of the Z event.

Pile-up Enriched sample The second method obtained by selecting events where photons have the closest distance to the second highest p_T vertex than the primary one, thus specifi-

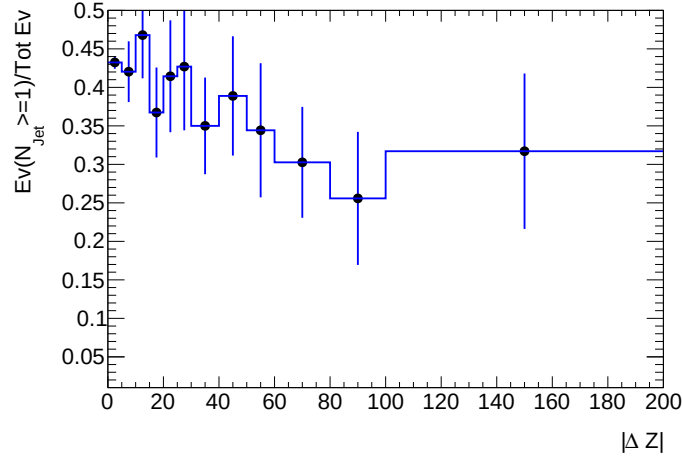


Figure 5-7 Fraction of events in data with a conversion in the ID with at least one jet as a function of Δz .

cally addressing pile-up characteristics. This sample is particularly developed for analyzing the kinematic properties of these events.

The systematic uncertainties depicted in Fig. 5-8, are assessed by evaluating the differences between the truth sample and the pile-up enhanced sample, which provides an accurate modelling of the pile-up background.

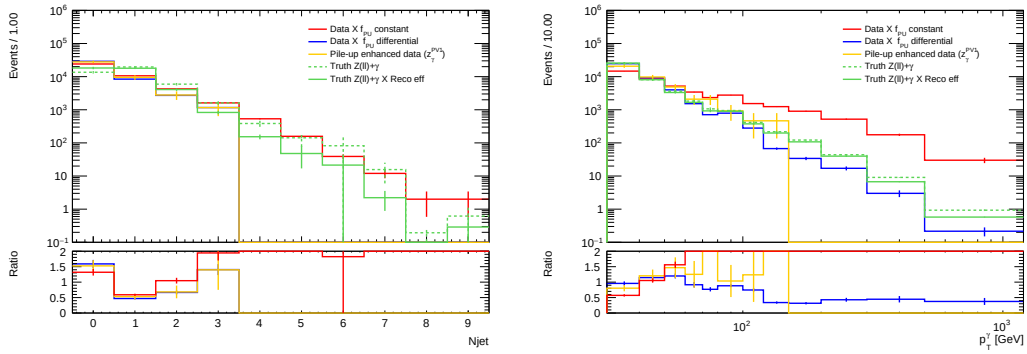


Figure 5-8 Comparison of the pile-up template shapes (truth in green, pile-up enhanced in yellow) with data scaled by f_{PU} (integral in red, differential in blue). The left panel shows N_{jet} , and the right panel shows p_T^γ . The bottom panels display the ratio to the truth distribution (solid green line). The left plot indicates that the data-driven estimate may not provide an accurate result due to the JVT bias.

5.3.4.3 $e\mu\gamma$ Control Region and other backgrounds

To effectively control and estimate the $t\bar{t}\gamma$ background, we constructed a dedicated Control Region (CR) which is dominated by $t\bar{t}\gamma$ events where it is easy to check the modelling. In this CR, we require a pair of charged leptons with Opposite Sign Different Flavor (OSDF) and a signal photon. All other selections applied in the SR are similarly applied in this CR for better isolation of $t\bar{t}\gamma$ background events. The predicted contribution of the $t\bar{t}\gamma$ background is scaled by a k factor of 1.44, derived from the ATLAS $t\bar{t}\gamma$ measurement^[167].

Additional small backgrounds include triboson events ($WW\gamma/WZ\gamma$) and diboson events where one lepton is misidentified as a photon ($WZ \rightarrow \ell\ell\ell\nu$ and $ZZ \rightarrow \ell\ell\ell\ell$). These account for approximately 1% of the total expected data and are thus estimated directly from Monte Carlo simulations. The uncertainty in the multi-boson processes is set to 30%, while for $t\bar{t}\gamma$ is set to be 15%. These uncertainties employed from normalizing the leading order (LO) prediction to the next-to-leading order calculation^[168].

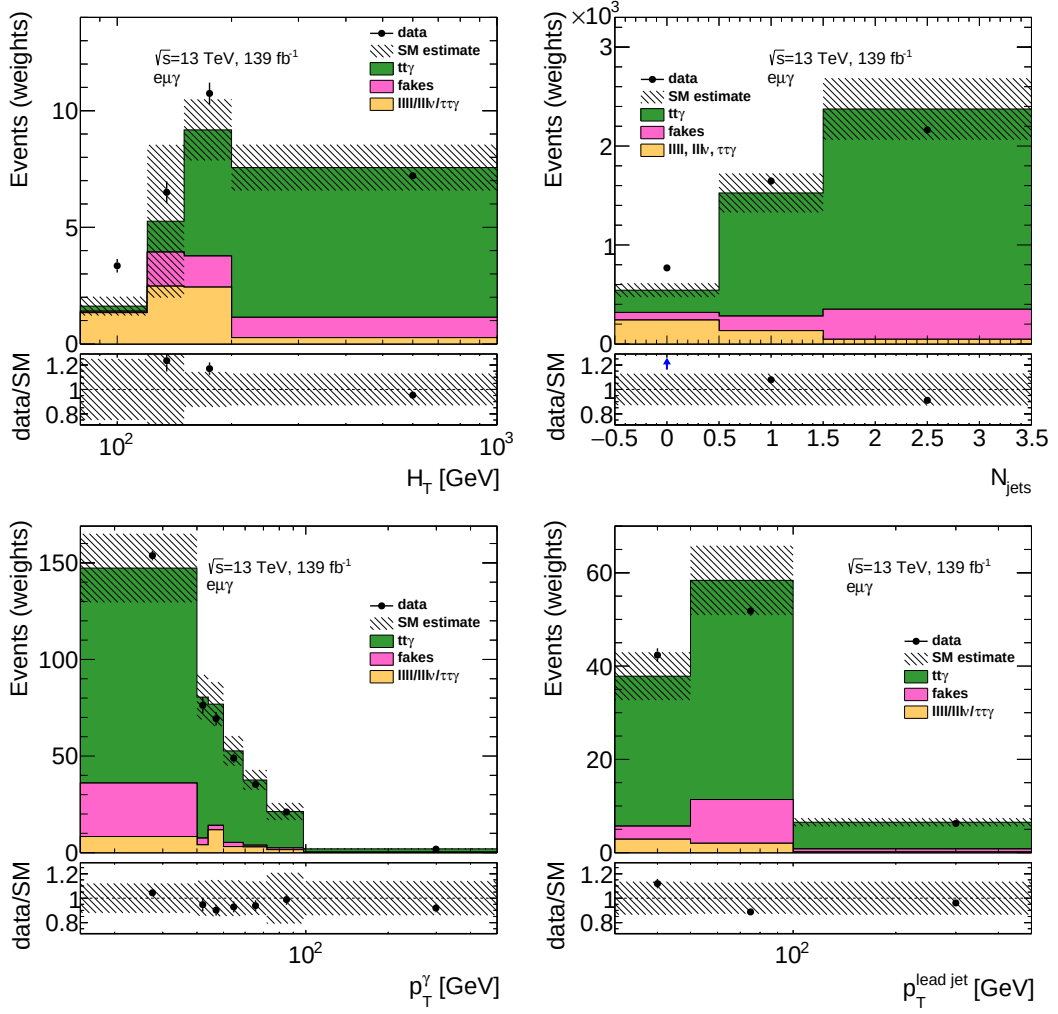
Good agreement between the data and MC is observed in most of bins for various kinematic variables in this CR and presented in Fig. 5–9, indicating the effectiveness of the estimation procedure.

However, significant discrepancies in the 0-jet bin and at low H_T are noted, primarily due to the mis-modelling of the $t\bar{t}\gamma$ sample (LO) at low jet multiplicity. These discrepancies are not problematic in the SR since both $t\bar{t}\gamma$ and multi-boson processes are more than an order of magnitude below the $Z\gamma$ signal in the 0-jet bin.

5.4 Systematic Uncertainties

5.4.1 Experimental uncertainties

These systematic uncertainties account for the finite resolution of objects reconstructed by the ATLAS detector and the modelling of reconstruction in the simulation. These uncertainties affect electrons, muons, photons, and jets, and are evaluated by adhering to the recommendations from various performance groups. These systematics are then propagated through the unfolding framework.

Figure 5-9 Comparison between data and MC in $e\mu\gamma$ CR.

Electron The uncertainties affecting electrons include variations in energy scale and resolution, evaluated by comparing the nominal case to a $\pm 1\sigma$ variation. Additional uncertainties related to the efficiency of electron identification, isolation, and trigger efficiencies, which are estimated by adjusting the Scale Factors^[169].

Muon The uncertainties for muon consider momentum resolution, including both the scale variation of momentum and smearing of ID and MS tracks with a $\pm 1\sigma$ variation. Further systematic on efficiency of reconstruction, identification, and isolation are accounted for by varying the Scale Factors^[170]. Trigger^[171] efficiency systematic are also included.

Photon Photon uncertainties encompass energy scale and resolution, assessed by a $\pm 1\sigma$ variation relative to the nominal case. Additional uncertainties involve the efficiency of identification and isolation, estimated by adjust the Scale Factors^[172].

Jet Jet uncertainties consider both the energy scale (JES) and resolution (JER)^[173]. Various options, differing by the number of nuisance parameters (NP), are available. This analysis uses the FullJER Category Reduction (R4_CategoryReduction_FullJER) set, which includes 30 JES NPs and 13 JER NPs. These systematics account for detector modelling, statistical effects, flavor composition, and pile-up jets. Additionally, Jet Vertex Tagging (JVT)^[174] efficiency systematics are included. Jet Flavor Composition^[175] and Jet Flavor Response are determined using a procedure which accounts for a more realistic gluon/light quark jet composition.

5.4.2 Theoretical uncertainties

Theoretical uncertainties^[176] in signal predictions arise from several impacts, including missing higher-order contributions in the cross-section calculation, uncertainties related to the choice of Parton Distribution Functions (PDFs), and uncertainties in the strong coupling constant (α_S). These uncertainties are quantified using weights from Sherpa 2.2.11 Monte Carlo samples. These variations are normalized to the same truth differential cross-section to avoid double counting.

Scale variations A primary source of theoretical uncertainty. These are addressed by varying the renormalization (μ_r) and factorisation (μ_f) factors used in the cross-section determination. A seven-point variation approach is employed, where μ_r and μ_f are varied in pairs as follows: $\{\mu_r, \mu_f\} \times \{0.5, 0.5\}, \{1.0, 0.5\}, \{0.5, 1.0\}, \{1.0, 1.0\}, \{2.0, 1.0\}, \{1.0, 2.0\}$, and $\{2.0, 2.0\}$. The uncertainty is assigned by taking the maximum deviation compared with nominal value in each bin as an envelope.

PDF variations Uncertainties come from PDF choice are considered following the PDF4LHC recommendations^[177]. The nominal PDF set NNPDF30_nnlo_as_0118 is compared with variations stored in the Sherpa samples.

α_S uncertainty The differences between nominal PDF set (NNPDF30_nnlo_as_0118) and varied PDF sets (NNPDF30_nnlo_as_0117 and NNPDF30_nnlo_as_0119) are taken as uncertainties that account for α_S uncertainty.

The resulting differences are propagated using varied migration matrices to access the impact on the unfolded results.

5.4.3 Unfolding uncertainties

The uncertainty in the unfolding process is evaluated by examining the potential bias introduced by the choice of the signal MC samples. To address this, a systematic uncertainty is estimated using a data-driven closure test. In this approach, the signal MC is reweighted to match the data, ensuring that the reconstructed-level MC aligns with the data post-background subtraction. The reweighted MC is then unfolded, using the same sample as pseudo-data and the transfer matrix from the original MC. The unfolding uncertainty is quantified by comparing the unfolded results of the reweighted MC to those of the nominal MC, with the differences representing the uncertainty. This procedure is conducted using the Bayesian method^[178] with two iterations, and various alternative methods are evaluated for consistency, with observed variations within 2%, as displayed in Fig. 5–10.

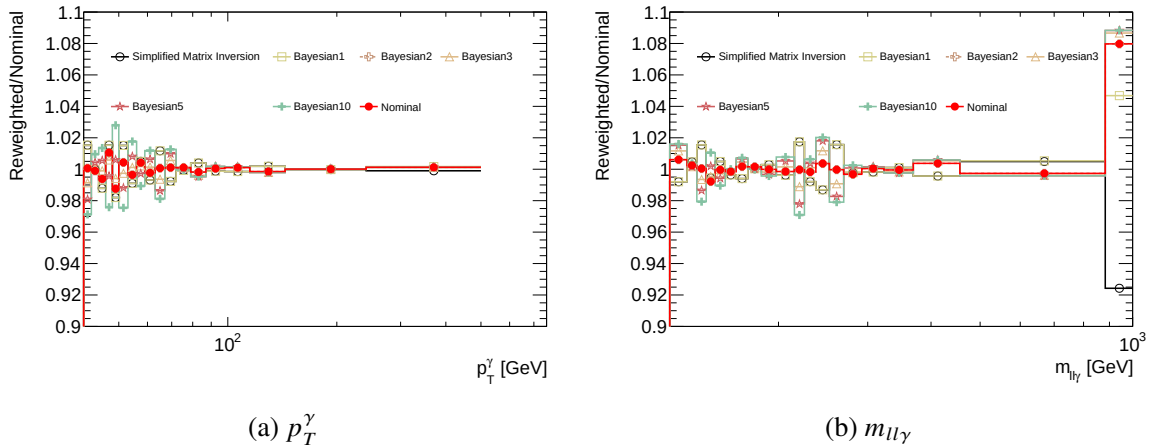


Figure 5–10 Ratio of unfolded results^[179] comparing the nominal MC sample to the reweighted MC sample. The nominal unfolding is performed using the Bayesian method with two iterations. Alternative unfolding methods with different iteration counts are also shown here.

5.4.4 Background uncertainties on data-driven estimation

The data-driven method utilized in the Z +jets background estimation involves careful considers both statistical and systematic uncertainties, and systematic uncertainties arise from various sources.

Apart from the luminosity, object reconstruction, and modelling related uncertainties discussed above, there are additional sources to account for the Z +jets background uncertainty. Signal leakage parameters introduce further uncertainties, particularly when different generators yields different results (e.g., SHERPA 2.2.11 vs. MADGRAPH). This discrepancy affects the leakage parameters, and, consequently, the Z +jets estimates. Moreover, the correlation factor R is influenced by the choice of anti-tight identification criteria and the value of the isolation gap. The uncertainty for anti-tight identification criteria is deduced by comparing different definitions (LoosePrime3, LoosePrime4, and LoosePrime5) as provided in Fig. 5–11. Similarly, the uncertainty associated with the choice of isolation gap is evaluated by changing the value of E_{gap} from 1 GeV to 3 GeV, illustrated in Fig. 5–12.

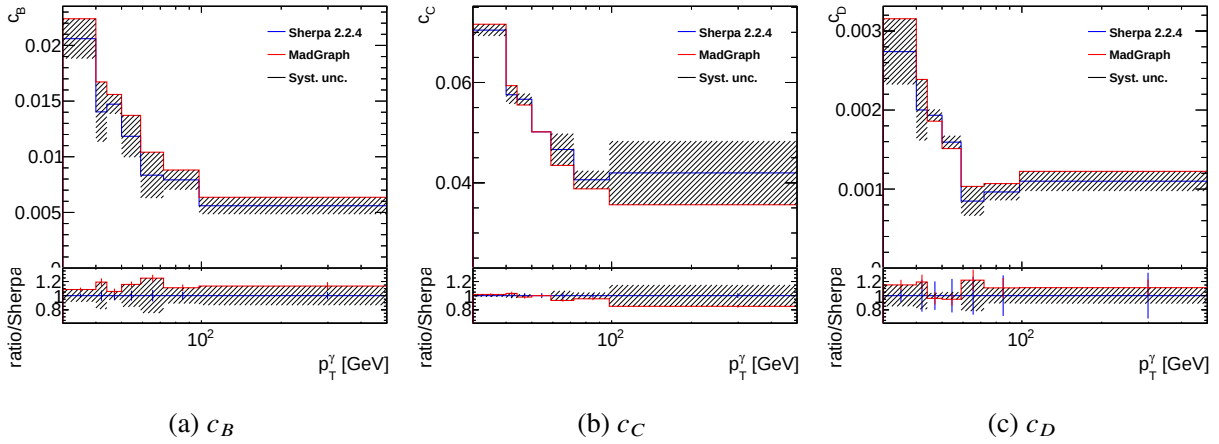


Figure 5–11 Signal leakage parameters^[179] c_X for varying the choice of generators.

The shaded band is calculated as:

$$\delta_{\text{generator}}^2 = (c_X(\text{MADGRAPH}) - c_X(\text{SHERPA}))^2.$$

These systematic uncertainties are propagated through the ABCD method, influencing the Z +jets estimates, and then propagated to the unfolding procedure.

5.4.5 Other uncertainties

Additional sources of systematics uncertainties impact the results, including:

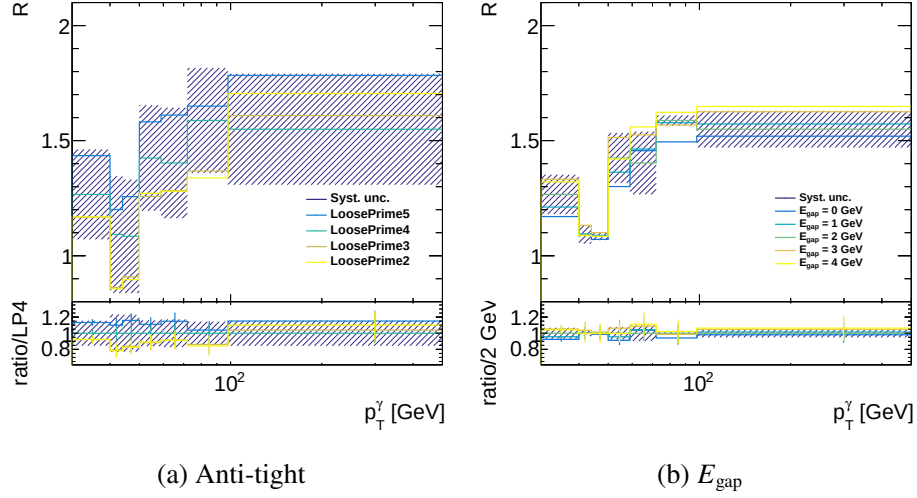


Figure 5–12 R factor for varing E_{gap} (left) and Anti-tight (right) definitions as function of $p_T^{\gamma[179]}$.

The shaded band is calculated as:

$$\delta_{\text{isolation gap}}^2 = (R(E_{\text{gap}} = 3 \text{ GeV}) - R(E_{\text{gap}} = 2 \text{ GeV}))^2 + (R(E_{\text{gap}} = 1 \text{ GeV}) - R(E_{\text{gap}} = 2 \text{ GeV}))^2$$

$$\delta_{\text{anti-tight}}^2 = (R(\text{LoosePrime5}) - R(\text{LoosePrime4}))^2 + (R(\text{LoosePrime3}) - R(\text{LoosePrime4}))^2$$

Pileup reweighting The pileup reweighting process involves contrasting the mean number of interactions per proton-proton collision ($\langle\mu\rangle$) in the data against those in simulated samples. The associated uncertainties are evaluated by varying the scaling factor applied to the data.

Luminosity The integrated luminosity uncertainty for the combined Run 2 dataset is assessed at 1.7%. This value is derived following the calibration methodology outlined in Ref.^[180], and propagated to all Monte Carlo samples.

5.4.6 Impact of systematics uncertainties

Systematic uncertainties are propagated to the unfolded results by employing different sets of inputs for the unfolding and migration matrices. This involves varying kinematics or weights by $\pm 1\sigma$ and comparing these results to the nominal case. The discrepancy between these results is treated as the uncertainty. The statistical uncertainty is assessed using pseudo-data (toys), which are fluctuated with a Poisson distribution centered around the bin nominal value, and the resultant difference is taken as the error.

Furthermore, Table 5–8 - 5–9 present a detailed breakdown of the impact of each individual systematic source utilized in the analysis as a function of number of jets. Fig. 5–13

- 5–14 illustrate the breakdown of systematic uncertainties in the unfolded distributions as function of various kinematic variables.

N_{jets}	0	1	2	≥ 3
Total Unc.	4.10	3.65	6.14	10.22
Statistical Unc.	0.50	0.85	1.45	2.45
Systematic Unc.	3.70	3.11	5.72	9.77
Luminosity Unc.	1.70	1.70	1.70	1.70
JET_BJES_Response	0.03	0.03	0.14	0.44
JET_EffectiveNP_Detector1	0.03	0.03	0.07	0.12
JET_EffectiveNP_Detector2	0.00	0.00	0.00	0.01
JET_EffectiveNP_Mixed1	0.02	0.02	0.04	0.07
JET_EffectiveNP_Mixed2	0.05	0.05	0.12	0.21
JET_EffectiveNP_Mixed3	0.02	0.03	0.06	0.08
JET_EffectiveNP_Modelling1	0.54	0.52	1.37	2.70
JET_EffectiveNP_Modelling2	0.03	0.03	0.07	0.10
JET_EffectiveNP_Modelling3	0.01	0.01	0.02	0.02
JET_EffectiveNP_Modelling4	0.00	0.00	0.01	0.02
JET_EffectiveNP_Statistical1	0.00	0.00	0.01	0.02
JET_EffectiveNP_Statistical2	0.07	0.07	0.16	0.28
JET_EffectiveNP_Statistical3	0.00	0.00	0.00	0.00
JET_EffectiveNP_Statistical4	0.00	0.00	0.00	0.00
JET_EffectiveNP_Statistical5	0.00	0.01	0.00	0.02
JET_EffectiveNP_Statistical6	0.01	0.01	0.02	0.04
JET_EtaIntercalibration_Modelling	0.61	0.57	1.59	3.07
JET_EtaIntercalibration_NonClosure_2018data	0.09	0.09	0.25	0.43
JET_EtaIntercalibration_NonClosure_highE	0.00	0.00	0.00	0.00
JET_EtaIntercalibration_NonClosure_negEta	0.02	0.03	0.02	0.04
JET_EtaIntercalibration_NonClosure_posEta	0.01	0.01	0.02	0.03
JET_EtaIntercalibration_TotalStat	0.15	0.17	0.35	0.67
JET_JER_DataVsMC_MC16	0.04	0.05	0.12	0.19
JET_JER_EffectiveNP_10	0.07	0.12	0.18	0.27
JET_JER_EffectiveNP_11	0.06	0.10	0.07	0.22
JET_JER_EffectiveNP_12restTerm	0.04	0.06	0.07	0.12
JET_JER_EffectiveNP_2	0.23	0.27	0.55	0.84
JET_JER_EffectiveNP_3	0.16	0.20	0.38	0.61
JET_JER_EffectiveNP_4	0.18	0.21	0.43	0.83
JET_JER_EffectiveNP_5	0.09	0.13	0.22	0.27
JET_JER_EffectiveNP_6	0.10	0.14	0.20	0.28
JET_JER_EffectiveNP_7	0.05	0.08	0.11	0.10
JET_JER_EffectiveNP_8	0.05	0.05	0.13	0.24
JET_JER_EffectiveNP_9	0.07	0.12	0.13	0.22
JET_JvtEfficiency	0.00	0.00	0.00	0.00
JET_Pileup_OffsetMu	0.29	0.24	0.73	1.59
JET_Pileup_OffsetNPV	0.47	0.45	1.18	2.33
JET_Pileup_PtTerm	0.05	0.06	0.13	0.24
JET_Pileup_RhoTopology	1.16	1.10	3.01	5.74
JET_PunchThrough_MC16	0.00	0.00	0.00	0.00
JET_SingleParticle_HighPt	0.00	0.00	0.00	0.00
JET_fJvtEfficiency	0.00	0.00	0.00	0.00
JET_Flavor_Composition	0.08	0.09	0.06	1.82
JET_Flavor_Response	0.74	0.75	1.82	3.61

Table 5–8 Breakdown of the impact from statistical, luminosity, and jet systematics in the N_{jet} distributions.

This table enumerates the individual contributions estimated across different jet bins from various systematic sources.

N_{jets}	0	1	2	≥ 3
EG_RESOLUTION_ALL	0.02	0.01	0.01	0.02
EG_SCALE_ALL	0.81	0.60	0.56	0.46
EL_EFF_ID_TOTAL_INPCOR_PLUS_UNCOR	0.60	0.60	0.62	0.67
EL_EFF_Iso_TOTAL_INPCOR_PLUS_UNCOR	0.02	0.03	0.03	0.04
EL_EFF_Reco_TOTAL_INPCOR_PLUS_UNCOR	0.11	0.12	0.12	0.13
MUON_EFF_ISO_STAT	0.07	0.10	0.12	0.14
MUON_EFF_ISO_SYS	0.18	0.18	0.19	0.20
MUON_EFF_RECO_STAT	0.06	0.06	0.06	0.06
MUON_EFF_RECO_STAT_LOWPT	0.02	0.02	0.00	0.02
MUON_EFF_RECO_SYS	0.19	0.21	0.23	0.26
MUON_EFF_RECO_SYS_LOWPT	0.02	0.02	0.00	0.02
MUON_EFF_TTVA_STAT	0.02	0.03	0.03	0.03
MUON_EFF_TTVA_SYS	0.03	0.03	0.04	0.04
MUON_ID	0.03	0.02	0.01	0.03
MUON_MS	0.02	0.02	0.01	0.02
MUON_SAGITTA_RESBIAS	0.04	0.03	0.02	0.01
MUON_SAGITTA_RHO	0.04	0.04	0.02	0.01
MUON_SCALE	0.08	0.06	0.08	0.06
PH_EFF_ID_Uncertainty	1.02	0.95	0.91	0.88
PH_EFF_ISO_Uncertainty	0.94	0.89	0.88	0.86
PRW_DATASF	2.05	0.77	0.21	0.29
PDF + Scale	0.48	0.13	1.16	0.77
Signal MC Stat Syst	0.10	0.17	0.31	0.40
dibosons	0.09	0.14	0.18	0.25
$WZ\gamma$	0.02	0.05	0.08	0.12
$WW\gamma$	0.04	0.06	0.09	0.12
$t\bar{t}\gamma$	0.01	0.34	1.57	3.43
$tW\gamma$	0.00	0.05	0.11	0.13
Z + jets	1.53	1.09	1.64	1.11
PU Background Background MC Stat Syst	0.46	0.16	0.04	0.00
Background MC Stat Syst	0.72	1.48	1.94	1.44

Table 5–9 Breakdown of the impact from object reconstruction, theoretical, and background systematics in the N_{jet} distributions.

This table enumerates the individual contributions estimated across different jet bins from various systematic sources, including electron, photon, muon, pileup reweighting and etc.

These tables and distributions reveal that the major sources of systematic uncertainties come from jet and background systematics uncertainties. Jet systematics uncertainties tend to be dominate for jet-related variables, while background systematics uncertainties remains dominant in non-jet-related variables. Jet systematics uncertainties are significantly influenced by flavor composition, flavor response uncertainty, and jet pileup rho topology. Conversely, background systematics uncertainties are predominantly influenced by Z+jets systematics uncertainties. In general, all other systematic uncertainties appear to have an impact of around 2% within the most of bins.

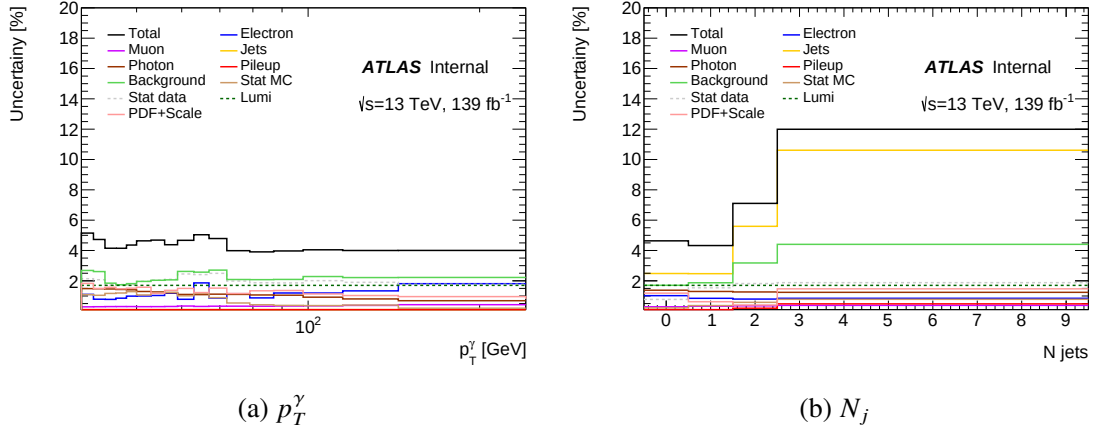


Figure 5–13 Breakdown of various systematic uncertainties^[179] after propagating to unfolding procedure as function of p_T^γ and N_j .

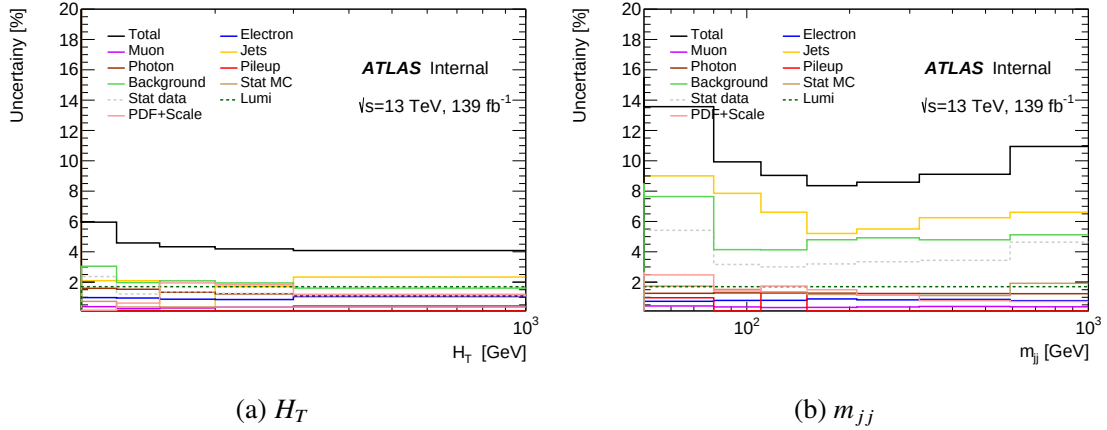


Figure 5–14 Breakdown of various systematic uncertainties^[179] after propagating to unfolding procedure as function of H_T and m_{jj} .

5.5 Fiducial Cross Section Measurements

Differential measurements examine the dependence of interaction probabilities on various kinematic variables. The process of unfolding is essential for correcting measured distributions for detector response, thereby recovering the particle-level distributions. The definition of the fiducial phase space is defined in this section, and built to be as close as possible to the detector level selection. Defining this volume is crucial for ensuring that the comparisons between data and theoretical predictions are reliable as much as possible.

5.5.1 Definition of Fiducial Region

The fiducial region definition includes only stable particles with a mean lifetime $c\tau > 10$ mm and "prompt" leptons (e and μ), excluding τ leptons as they are treated as background. Photons are also included if they do not originate from hadron decay. Leptons are "dressed" by adding the momentum of all photons within a cone of $\Delta R < 0.1$ around them.

Leptons must meet the transverse momentum (p_T) requirements of the signal region (SR) that $p_T(\ell_1) > 30$ GeV and $p_T(\ell_2) > 25$ GeV. The pseudorapidity (η) requirements are less strict, with $|\eta(\ell)| < 2.47$ for both electrons and muons. Photons are required to have $p_T(\gamma) > 30$ GeV and $|\eta(\gamma)| < 2.47$. At the truth level, photon isolation is ensured by requiring the scalar sum of the transverse energies of all particles (excluding muons and neutrinos) within a core of $\Delta R = 0.2$ around the photon to be less than 7% of E_T^γ . This criterion is optimized to achieve consistent acceptance between reconstruction and truth levels. Additionally, photons are excluded if they are within a cone of $\Delta R = 0.4$ around any lepton. Jets follow the same criteria as in the SR so that for central jets ($|\eta| < 2.5$) must have $p_T > 30$ GeV, while forward jets ($2.5 < |\eta| < 4.5$) must have $p_T > 50$ GeV. This selection strikes a balance between minimizing pile-up jets and maintaining good statistics at low p_T ^[181]. Moreover, jets are also excluded if they lie within $\Delta R = 0.4$ of a photon.

To suppress final state radiation (FSR) events, two invariant mass selections are employed: $m(\ell\ell) > 40$ GeV and $m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV. A comprehensive summary of all fiducial cuts utilized in this measurement is provided in Table. 5–10.

Quantity	Selection
lepton cuts	$p_T(\ell_1) > 30$ GeV, $p_T(\ell_2) > 25$ GeV, $ \eta(\ell) < 2.47$
photon cuts	$p_T(\gamma) > 30$ GeV, $ \eta(\gamma) < 2.37$, $\Delta R(\gamma, \ell) > 0.4$
photon isolation	$E_T^{\text{cone20}}/E_T^\gamma < 0.07$
jet cuts	$p_T > 30$ GeV if $ \eta < 2.5$ $p_T > 50$ GeV if $2.5 < \eta < 4.5$, $\Delta R(\gamma, \text{jet}) > 0.4$
mass cuts	$m(\ell\ell) > 40$ GeV, $m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV

Table 5–10 Fiducial region definitions.

5.5.2 Fiducial Cross Section

The correction factor^[182-183] C is a vital component in the accurate determination of the fiducial cross-section. This factor corrects for inefficiencies and resolution limitations of the

detector, ensuring that the measurements accurately represent particle-level interactions. By accounting for these imperfections, C enhances the reliability and precision of the calculated cross-section.

The calculation of the correction factor C involves a comparison between the number of signal events that pass all selection criteria at the detector level and the number of signal events at the particle level within the fiducial volume, as determined by Monte Carlo (MC) simulations. Specifically, C is the ratio of MC-reconstructed signal events to the generated particle-level events:

$$\sigma^{fid} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times L} \quad (5-7)$$

where term N_{obs} and N_{bkg} represent the observed number of events and the expected number of background events, respectively. L denotes the luminosity, while C is the correction factor. This ratio adjusts for any losses and distortions in the event data caused by detector acceptance.

In this analysis, C is derived using the SHERPA samples, incorporating events both from ee and $\mu\mu$ channels. The inclusive C factor is measured to be $0.543 \pm 0.001(\text{stat.})$, representing the proportion of signal events that are accurately reconstructed and identified by the detector.

5.5.3 Procedure of Unfolding

In this section, we will explore the concepts of unfolding and differential cross-section measurements. Unfolding is crucial for correcting distortions caused by detector effects and essential for the accurate determination of differential cross sections. By employing unfolding, we aim to obtain reliable and interpretable results that potentially confirming the theoretical predictions.

5.5.3.1 Introduction to Unfolding

Unfolding is a crucial procedure that enables the comparison of measured results with other experiments or theoretical predictions by converting detector-level observables to particle-level observables. This transition is necessary because typical measurements are influenced by three main effects: detector effects, statistical fluctuations, and background events. This process, known as "Unfolding"^[178,184], corrects the distortions and inefficiencies from the detector response.

Detector effects involve the limited precision and efficiency of the detector in measuring

properties, which may lead to events being incorrectly reconstructed or missed altogether.

Statistical fluctuations arise since the observed number of events follows a Poisson distribution, introducing inherent variability and commonly quantified as the square root of the event count.

Background events are those that resemble the signal but originate from different processes, complicating the accurate determination of the signal events.

Among the various methods available for unfolding, the iterative Bayesian Unfolding^[185] technique is particularly effective and employed in this analysis. This method iteratively refines the estimates of the truth distributions, two iterations are used as the nominal value to minimize the bias while considering statistical error.

Iterative Bayesian Unfolding The Iterative Bayesian Unfolding (IBU) method^[186], refines the estimates of the truth distribution by balancing bias reduction and statistical uncertainty, and is a sophisticated method designed to address these challenges.

Iterative Bayesian Unfolding begins with an initial guess of the truth distribution, normally derived from prior knowledge or Monte Carlo simulations. The unfolding process iteratively refines this estimate ($x^{(n)}$), with each iteration improving upon the previous one. The update rule used in the EM (Expectation-Maximization) algorithm^[187] is given by:

$$x_j^{(n+1)} = x_j^{(n)} \sum_{i=1}^M \frac{A_{ij}}{\epsilon_j} \frac{y_i}{\sum_{k=1}^N A_{ik} x_k^{(n)}} \quad (5-8)$$

where $x_j^{(n)}$ represents the current estimate of the truth distribution, y_i is the observed data, A_{ij} is the response matrix element, and the ϵ_j is the detection efficiency for bin j . The detailed explanation for various inputs in the unfolding procedure is described in the next section. The EM algorithm has two significant properties: it guarantees positive solution given positive initial values and measurements, and it maximizes the likelihood function for independent Poisson-distributed measurements. However, the convergence rate can be slow, with the number of iterations needed growing quadratically with the number of bins. To address this, the number of iterations is typically fixed, and initial values based on Monte Carlo simulations are used to regularize the results.

An alternative method is the Iterative Dynamically Stabilized (IDS) method^[188], which combines elements of the EM iterative procedure with bin-by-bin unfolding. It employs

non-linear weighting factors to enhance convergence speed and data normalization. Unlike the EM method, which can require numerous iterations, the IDS method typically achieves accurate results with fewer iterations, making it more efficient in certain scenarios.

Iterative Bayesian Unfolding (IBU), particularly using the EM algorithm, offers a systematic approach to refining truth distribution estimates from observed data. The IBU method systematically refines truth distribution estimates from observed data by utilizing a novel adaptation of the response matrix and observed data. This method not only updates estimates iteratively but also integrates specific innovations to ensure reliable results. The incorporation of fiducial and efficiency corrections, along with alternative methods like IDS, further enhances the accuracy and robustness of the unfolding process.

5.5.3.2 Unfolding Inputs

The primary inputs^[184] for the unfolding process are as follows:

- **Reconstructed Distribution:** This involves the target observables for both data and each combined background predictions, filled with events that pass the reconstructed-event selection criteria at the reconstructed level, weighted by the reconstructed-event weight.
- **Fiducial Correction:** This factor corrects for events that fall outside the detector phase space. This fiducial correction numerator is filled with events passing both the truth-event and reconstructed-event selections at the reconstructed level, weighted accordingly. The denominator includes events passing the reconstructed-event selection at the reconstructed level with the same weight. The fiducial correction (C_{fid}) can be expressed as:

$$C_{fid,i} = \frac{N_i^{SR\&\&FR}}{N_i^{FR}} \quad (5-9)$$

where N_i^{SR} represents the number of events at reconstruction level in the signal region (SR) in bin i , and N_i^{FR} denotes the number of events at the truth level in the fiducial region in bin i ,

- **Efficiency Correction:** This corrects for the imperfect efficiency of the detector reconstruction capabilities. The efficiency correction numerator includes events that meet both the truth-event and reconstructed-event selections at the truth level, weighted by the reconstructed-event weight. The denominator contains events passing the truth-

event selection at the truth level with the truth-event weight. The efficiency correction ($\epsilon_{cor,i}$) can be written as:

$$\epsilon_{cor,i} = \frac{N_i^{SR\&\&FR}}{N_i^{SR}} \quad (5-10)$$

- **Purity:** This is defined as the fraction of events within a specific bin at the reconstructed level that are also found within the same bin at the truth level.
- **Migration Matrix:** A two-dimensional histogram that records events passing both the truth-event and reconstructed-event selections. This is filled with reconstructed values on the x-axis and truth value on the y-axis, weighted by the reconstructed-event weight.

All these inputs are derived from Monte Carlo (MC) samples. Fig. 5–15 illustrates the fiducial and efficiency corrections for SHERPA 2.2.11 $Z\gamma$ MC samples as a function of variables, such as p_T^γ , N_j , H_T , m_{jj} , $\cos \theta_{CS}$, and ϕ_{CS} . Migration matrices for the same set of variables are presented in Fig. 5–16.

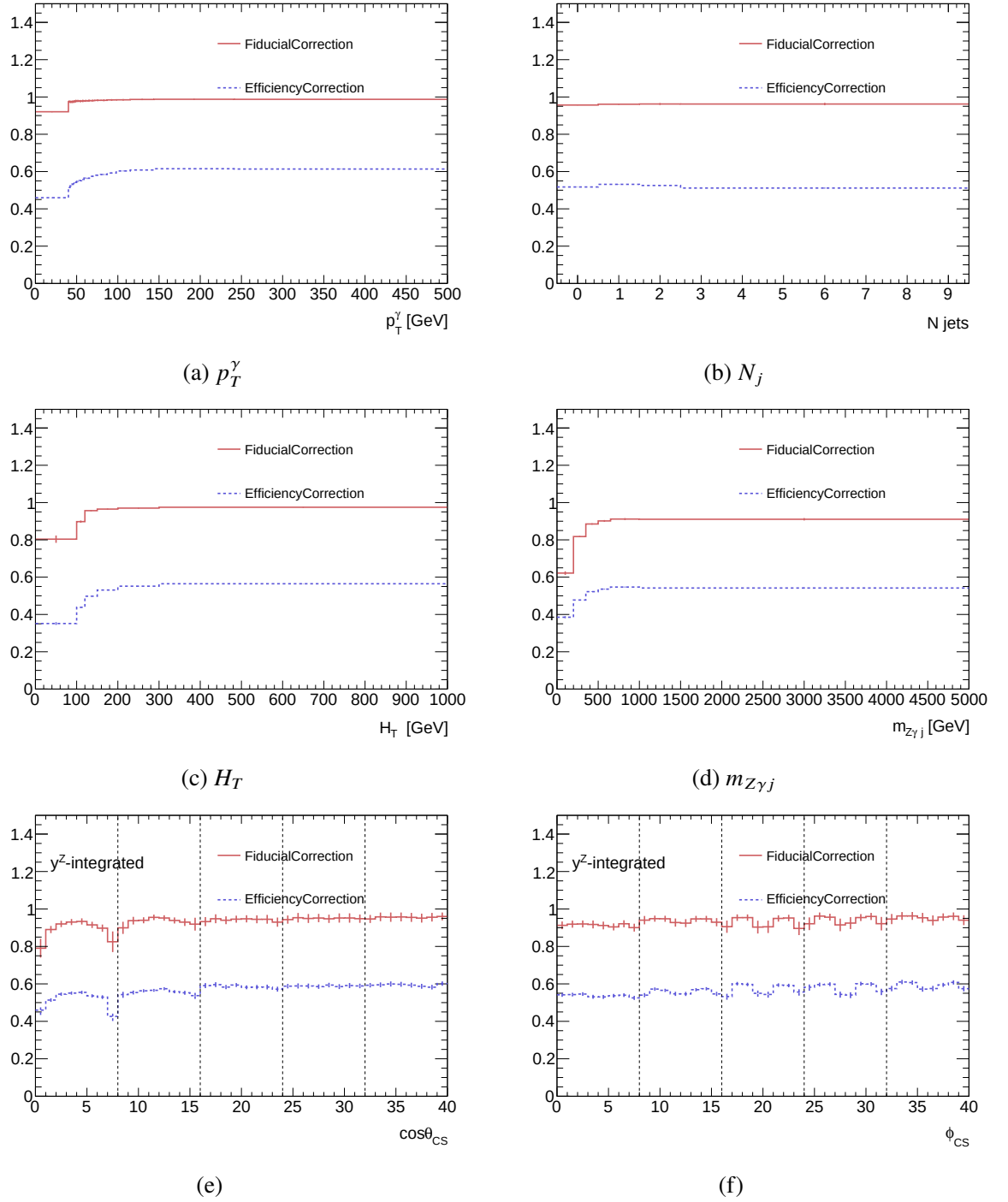


Figure 5–15 Fiducial correction and Efficiency correction^[179] as functions of different kinematic variables (p_T^γ , N_j , H_T , m_{jj} , $\cos \theta_{CS}$, and ϕ_{CS}) used in the unfolding. $\cos \theta_{CS}$ and ϕ_{CS} are polarization 2D variables but structured into 5×8 bins as introduced in Section .

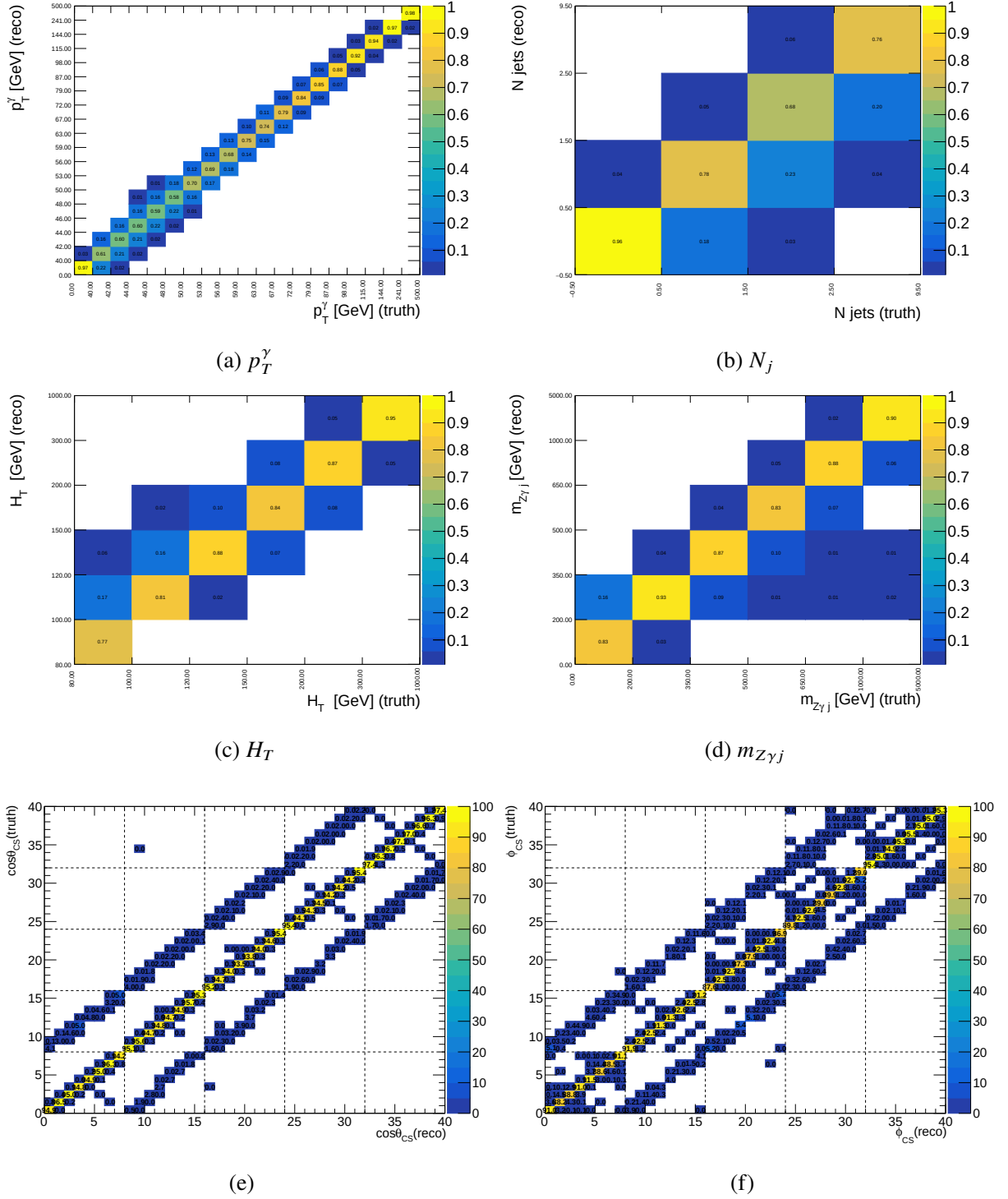


Figure 5–16 Migration matrices^[179] for different kinematic variables used in the unfolding. $\cos \theta_{CS}$ and ϕ_{CS} are polarization 2D variables but structured into 5×8 bins as introduced in Section .

An unfolding closure test is a pivotal validation procedure, designed to assess the accuracy of an unfolding method. This test involves generating a known truth distribution using Monte Carlo (MC) simulations and simulating detector effects to produce a corresponding reconstructed distribution. The unfolding algorithm is then applied to the reconstructed data to retrieve the unfolded distribution, which is compared to the original truth distribution. The agreement between the unfolded and truth distribution is critical for validating the ability to accurately correct for detector effects of the unfolding method. This process ensures that the method reliably reconstructs the truth particle-level information from observed data, providing confidence in the application to real experimental measurements.

Fig. 5–17 displays the closure test of the unfolding process, where the same SHERPA 2.2.11 MC, used as the prior in the unfolding, is applied to data with background subtracted. The closure test shows good agreement across all variables within the entire spectrum.

5.5.3.3 Unfolding

In this section, we present the results obtained using real experimental data. The unfolded results demonstrate the alignment between the data and the theoretical predictions.

Fig. 5–18 present the unfolded data, utilizing SHERPA 2.2.11 as the signal for the $Z\gamma$ process. Statistical uncertainties in the data are propagated through the unfolding process using MC toys, with 1000 pseudo-experiments conducted by fluctuating each bin according to the Poisson distribution of the data within the bin. For each pseudo-experiment, the unfolding procedure is repeated, and the RMS of the results in each bin is used to quantify the error. Statistical errors on the MC (signal and background) are similarly propagated. Experimental systematics are addressed by repeating the unfolding for each variation and summing them in quadrature.

The predictions from SHERPA 2.2.11 exhibit a general underestimation factor of 0.92, although the shape distributions correspond well with the observed data. Jet variables also appear to be well-modelled overall.

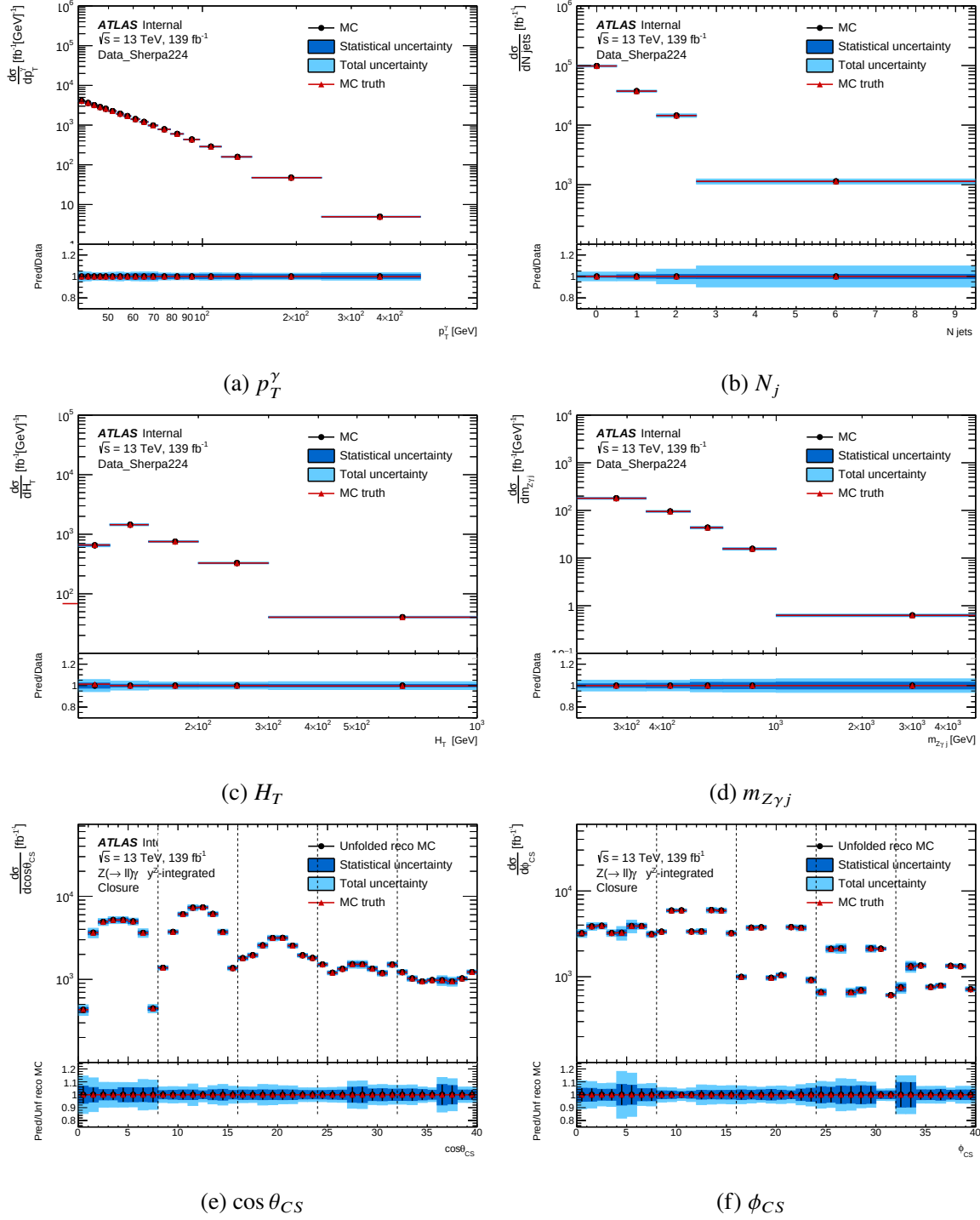


Figure 5–17 Unfolding closure^[179]. The Data is constructed by combining Monte Carlo (MC) background and MC signal from SHERPA 2.2.11, utilizing Iterative Bayesian Unfolding with two iterations.

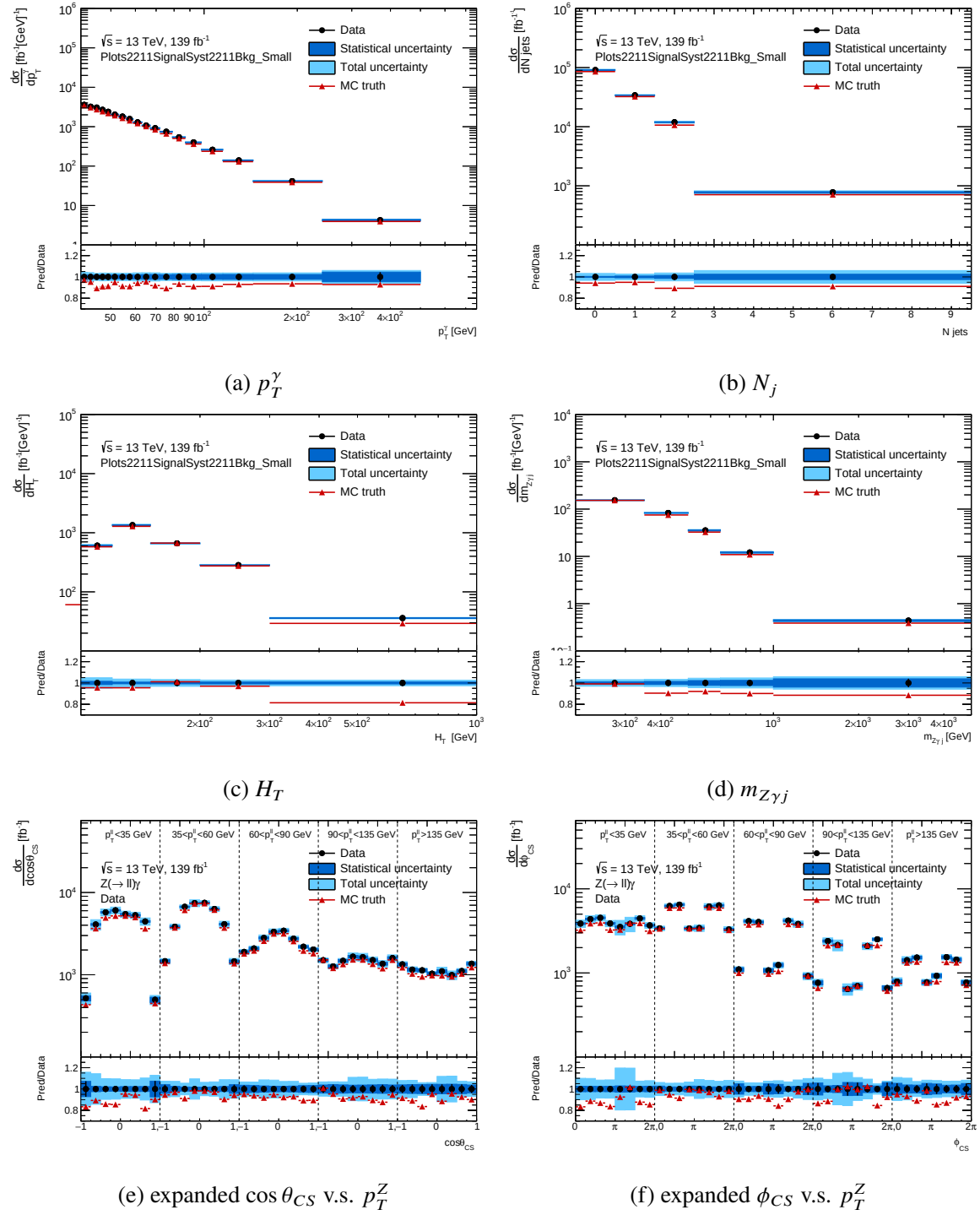


Figure 5-18 Unfolded results^[179] for real experimental data compared to predictions of SHERPA 2.2.11 as signal.

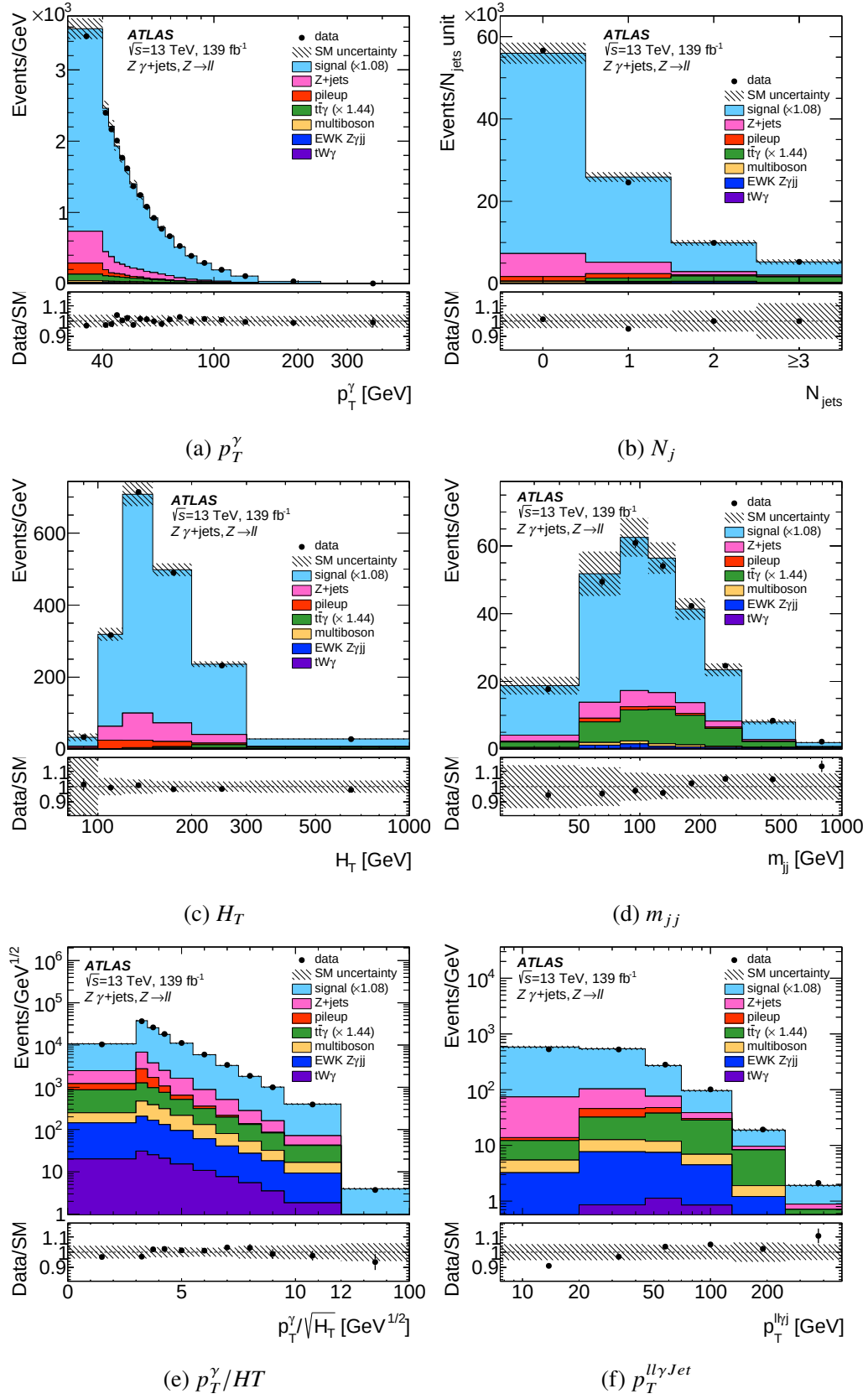
5.6 Results

The contributions and their uncertainties for each prediction source within the Signal Region (SR) are listed in Table. 5–11.

Source	$ee + \mu\mu$
Signal	79392 ± 56 (stat.) ± 2277 (syst.)
Z+jets	9773 ± 465 (stat.) ± 2134 (syst.)
$t\bar{t}\gamma$	3609 ± 14 (stat.) ± 541 (syst.)
Pileup	2510 ± 72 (stat.) ± 698 (syst.)
diboson	947 ± 5 (stat.) ± 160 (syst.)
$tW\gamma$	148.2 ± 0.6 (stat.) ± 44.5 (syst.)
Total prediction	96382 ± 474 (stat.) ± 3248 (syst.)

Table 5–11 Contribution and uncertainties for each source. The systematic uncertainties for $tW\gamma$, diboson, and $t\bar{t}\gamma$ include background uncertainties. For Z+jets, the systematic uncertainties encompass the propagation of background uncertainties, E_{gap} and anti-tight criteria, and generator uncertainties. The signal systematic uncertainties represent the experiment uncertainties. These yields were obtained using SHERPA 2.2.11 for the signal.

Fig. 5–19 provides a comparison between the observed data and the expected SM events for the $Z\gamma$ process, utilizing SHERPA 2.2.11. As shown in Fig. 5–18 the signal sample underestimated the data by a factor of 0.92, and is subsequently scaled by 1.08 to achieve better concordance. Generally, a good agreement between the data and MC predictions is observed, though some discrepancies exist. The discrepancies are anticipated to be addressed by incorporating theoretical uncertainties not currently reflected in the uncertainty band.

Figure 5-19 Comparison^[189] of data and MC predictions in the SR.

5.6.1 Comparison with Various Predictions

This section presents a detailed comparison of several differential distributions for $Z\gamma$ production in association with jets, focusing on the final state where the Z boson decays into two opposite-sign same flavor leptons (ee or $\mu\mu$). The results are compared with both Monte Carlo (MC) predictions and fixed-order calculations, such as MATRIX^[147,190], as well as recent results from MiNNLO_{PS}^[191].

Fig. 5–20 - 5–24 compare the unfolded results with various theoretical predictions, including SHERPA samples (2.2.4 and 2.2.11) and MADGRAPH samples. Additionally, predictions from MiNNLO_{PS} are included. Fixed-order calculations using the MATRIX software (with CT14^[192] PDF set at NNLO in pQCD) are also considered. A good overall agreement observed between the unfolded data and various theoretical predictions. Corrections are employed to align with particle-level MC results as the MATRIX predictions are obtained at the Born level, and are derived by comparing differential cross-sections obtained with and without hadronization and underlying event effects. Moreover, non-perturbative effects have been taken into account when comparing fixed-order calculations and MC at the particle-level, especially applied solely to jet variables. The MC generator used for these correction is MADGRAPH_AMC@NLO, interfaced with PYTHIA8 using the ATLAS A14 tune^[193]. Jets are computed using the anti- k_t algorithm^[126] with a radius parameter of $R = 0.4$, constructed from stable particles or partons after showering.

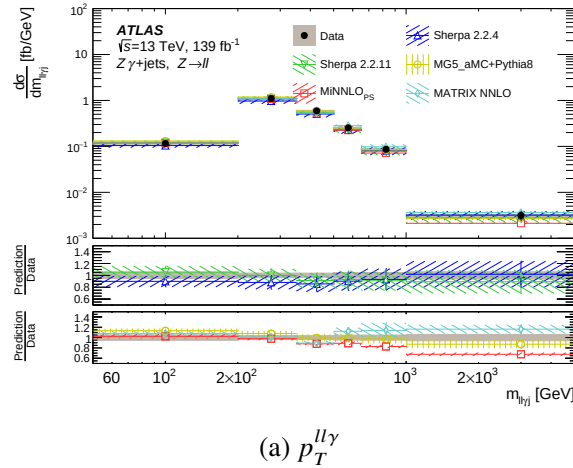


Figure 5–20 Comparison^[189] of theoretical predictions (SHERPA 2.2.4, SHERPA 2.2.11, MADGRAPH, MiNNLO_{PS}, and MATRIX NNLO calculations.)

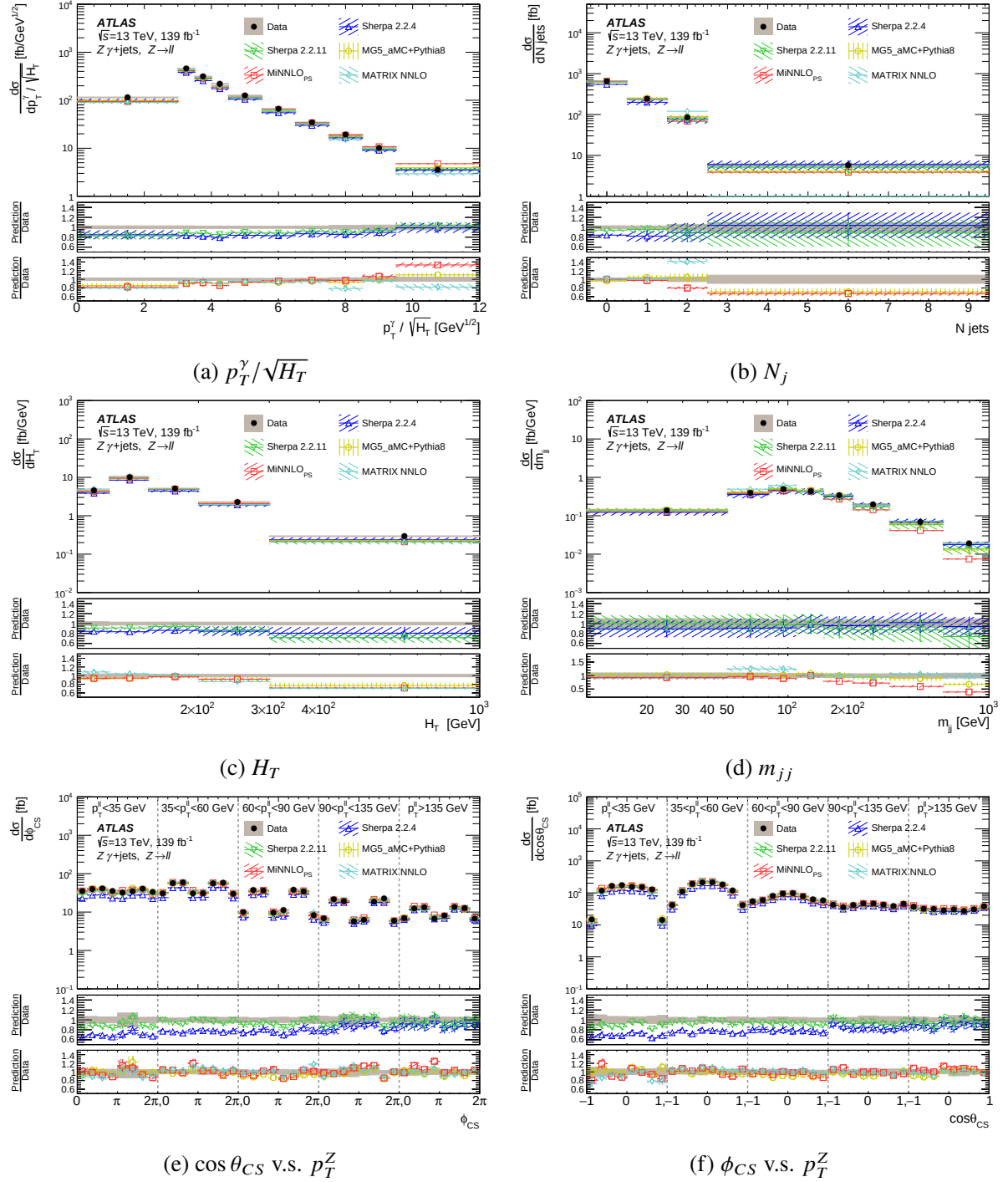


Figure 5-21 Comparison^[189] of theoretical predictions (SHERPA 2.2.4, SHERPA 2.2.11, MADGRAPH, MiNNLP_{PS}, and MATRIX NNLO calculations.)

The detailed comparison of unfolded results with various theoretical predictions provide crucial insights into the accuracy and reliability of different models. SHERPA, MADGRAPH,

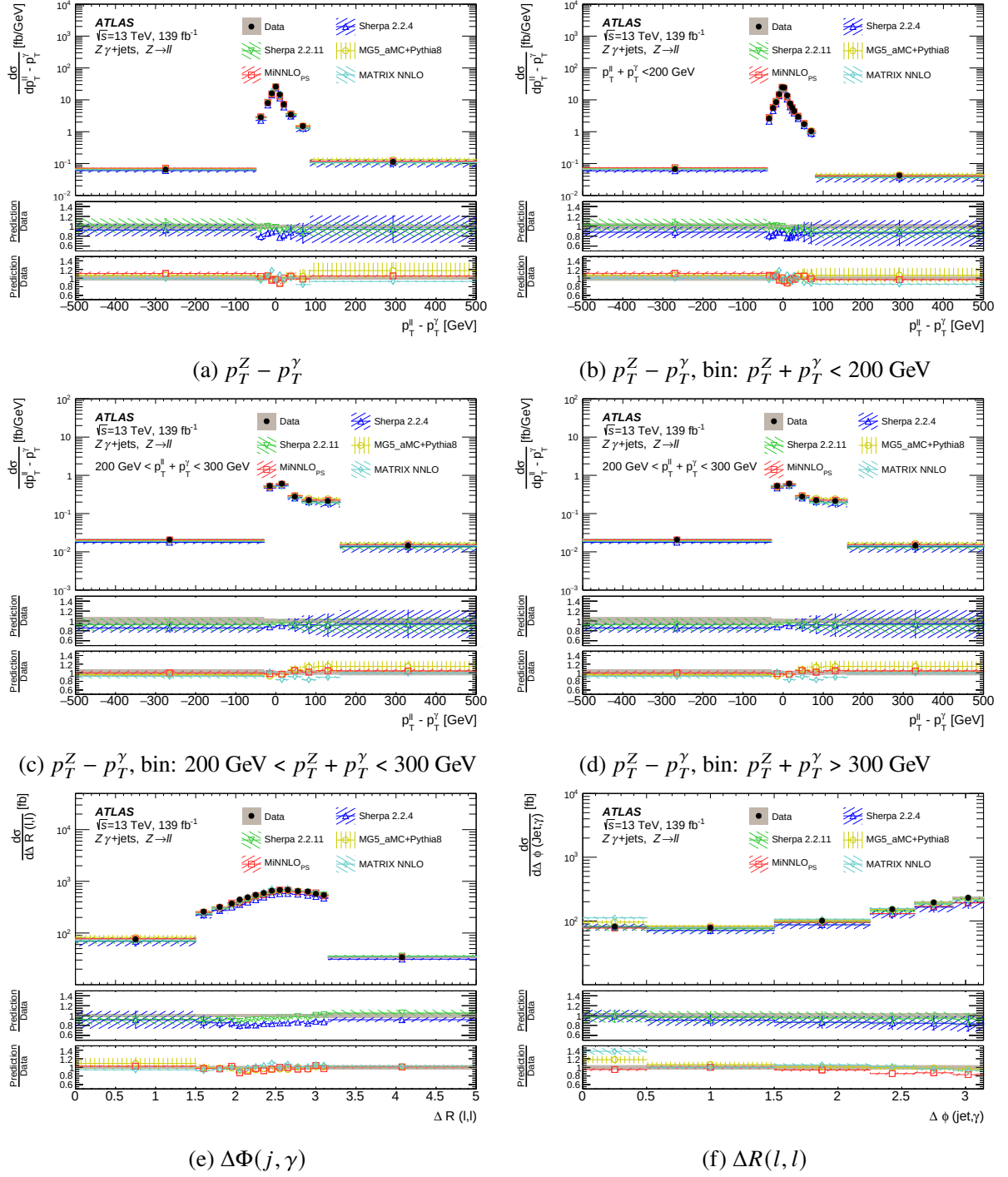


Figure 5–22 Comparison^[189] of theoretical predictions (SHERPA 2.2.4, SHERPA 2.2.11, MADGRAPH, MiNNLO_{PS}, and MATRIX NNLO calculations.)

MiNNLO_{PS}, and MATRIX each display unique advantages and contribute to a more comprehensive understanding of $Z\gamma$ production in association with jets. These results help constrain

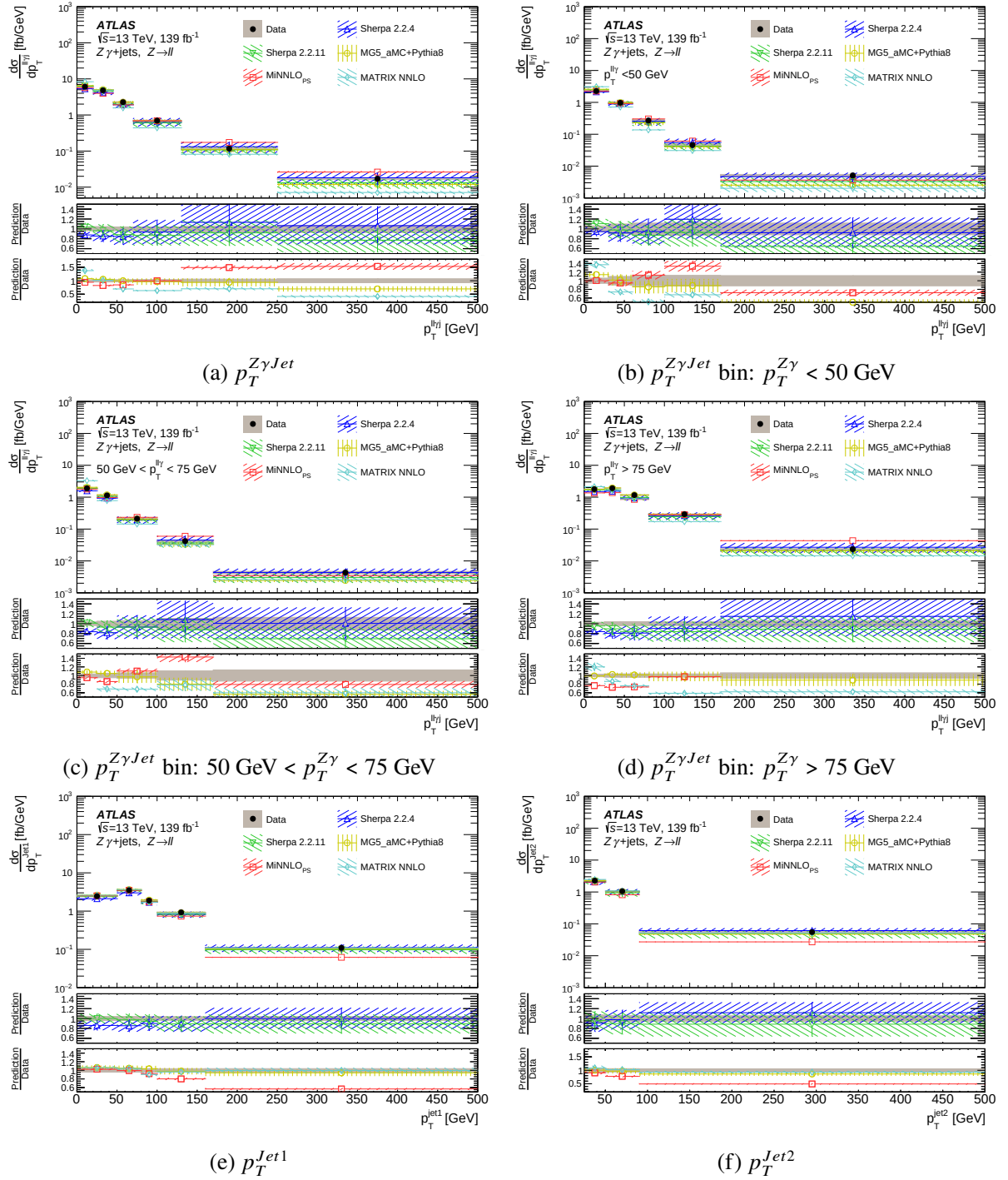


Figure 5-23 Comparison^[189] of theoretical predictions (SHERPA 2.2.4, SHERPA 2.2.11, MADGRAPH, MiNNLO_{PS}, and MATRIX NNLO calculations.)

beyond the SM predictions, including effective field theory (EFT), and enhance the precision of QCD predictions.

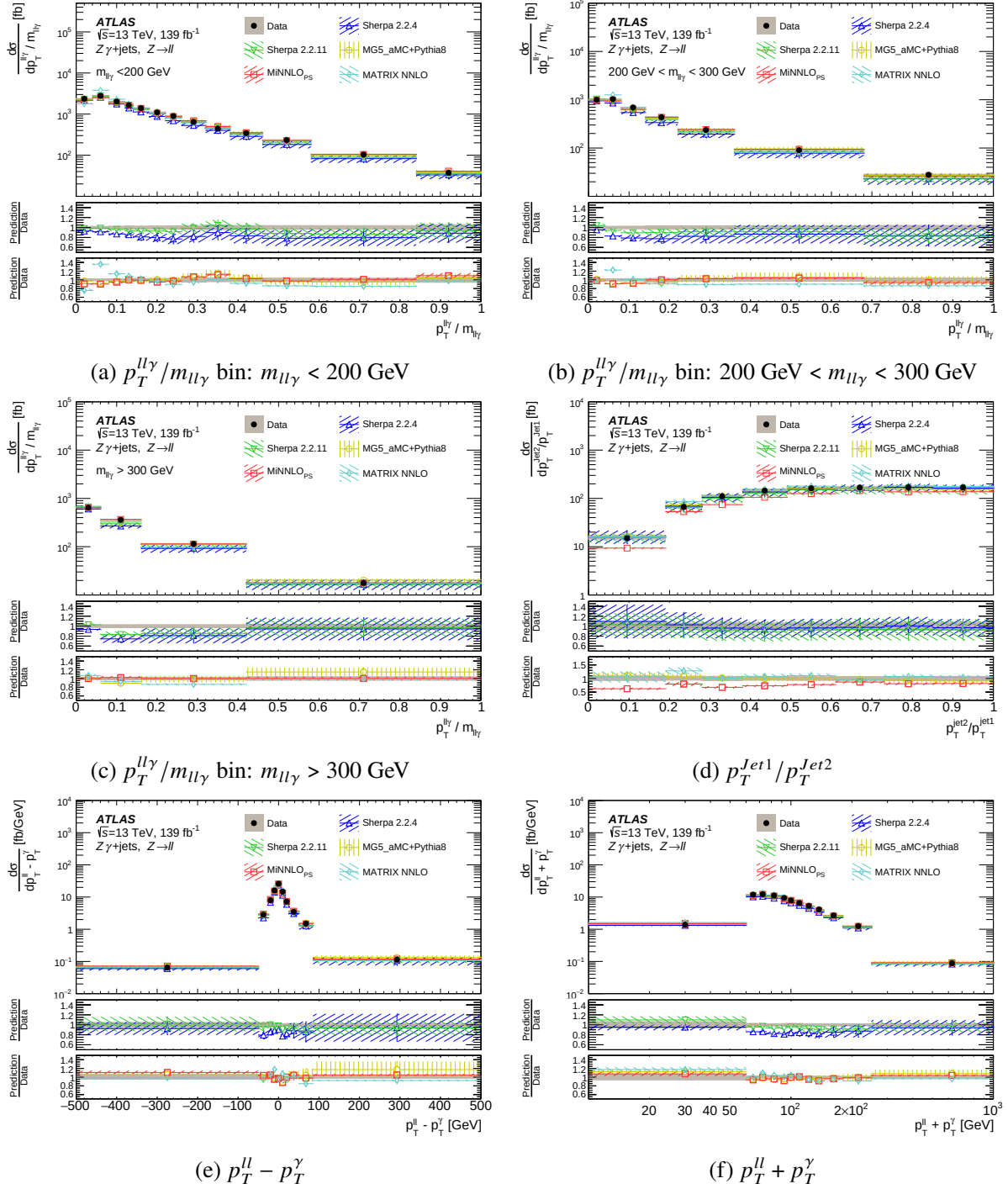


Figure 5–24 Comparison^[189] of theoretical predictions (SHERPA 2.2.4, SHERPA 2.2.11, MADGRAPH, MINNLO_{PS}, and MATRIX NNLO calculations.)

Chapter 6 Search for Anomalous Neutral Triple Gauge Couplings in $Z\gamma$ Production

The previous chapter presents differential measurements of $Z\gamma$ production in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV, using 139 fb^{-1} of data collected by the ATLAS detector during full Run-2. This chapter, building upon previous Standard Model $Z\gamma$ measurements, further explores neutral Triple Gauge Couplings (nTGCs) constraints by focusing on events where the Z boson decays into pair of charged leptons, with the transverse momentum of leading photon above 200 GeV and pseudorapidity within the region of $|\eta| < 2.37$. The selection criteria ensure the leptonic decay products of the Z boson are Opposite Sign and Same Flavor (OSSF), confirming their origin from an on-shell Z boson.

A key advance in this study is the successful alignment of dimension-8 nTGC operators with form factors from the effective vertex function approach, enabling an efficient translation of bounds from form factors to dimension-8 nTGC operators. This marks the first presentation of data results based on this innovative nTGC formulation, which significantly contributes to the ongoing validation of theoretical predictions and the exploration of potential new physical phenomena.

6.1 Introduction

The precision measurements at the Large Hadron Collider (LHC) play a pivotal role in enhancing the understanding of the Standard Model (SM), particularly in the realm of electroweak interactions, and probing for new physics possibilities. This chapter describes a follow-up study built upon chapter 5, the precise measurements of $Z\gamma$ production where Z bosons decay into charged leptons, providing an ideal path to search for new phenomena beyond the SM. This research not only allows for the fully reconstruction of final states with high precision, but also offers a window into phenomena not included by the SM, such as neutral Triple Gauge Couplings (nTGCs)^[10,13-14].

The LHC data collected from 2015 to 2018 is utilized to perform the measurements and also to explore nTGCs, which uniquely emerge at the dimension-8 level of the Standard Model

Effective Field Theory (SMEFT)^[7]. This analysis focuses exclusively on these dimension-8 operators, which are relevant to explore new interactions in this channel to potentially indicate new physics. These dimension-8 operators, although suppressed by the power of the new physics scale (Λ^{-4}), providing a powerful tool for extending the reach of current physical theories. Moreover, the incorporation of the SMEFT represents a significant methodological advancement in this study. SMEFT extends the Standard Model integrating refinements to the theoretical framework used to interpret complex experimental data, enhancing the detection sensitivity for searching new phenomena.

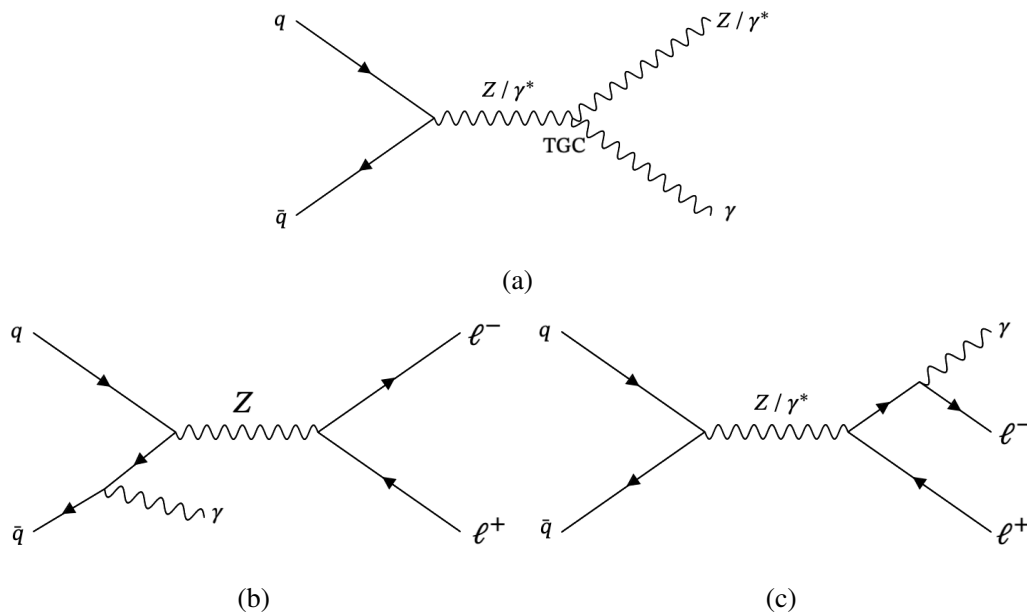


Figure 6–1 Illustration of $Z\gamma$ production through various modes.

Diagram (a) shows $Z\gamma$ production through neutral triple gauge couplings (nTGCs), diagram (b) indicates the process involving initial state radiation (ISR) photon, and the diagram (c) presents the production involving final state radiation (FSR) photon.

This analysis is conducted considering the Feynman diagrams, as illustrated in Fig. 6–1 that demonstrate the production of $Z\gamma$ through various mechanisms, including neutral triple gauge couplings, initial state radiations and final state radiations. This study marks a pioneering achievement as it presents the first data results employing the latest nTGC formulation^[13–14]. A critical aspect of this work is the successful establishment of the nontrivial mapping relationship between the SMEFT and the Effective Vertex Approach, which respect the full electroweak gauge group $SU(2)_L \oplus U(1)_Y$ of the SM, ensuring the relationship with

the physical cut-off scales through three independent form factors (h_i^V). This advancement allows for a better motivated interpretation of the LHC data, and ensures consistent form factors derived from those dimension-8 operators in the SMEFT framework.

Additionally, the analysis includes precise measurements of the photon transverse momentum and the unfolded distribution is used for EFT limit setting. Six dimension-8 operators (O_{G+} , O_{G-} , O_{BB} , $O_{\tilde{B}W}$, O_{BW} , O_{WW}) are studied, with a focus on constraining the coefficients (C_{G+} , C_{G-} , C_{BB} , $C_{\tilde{B}W}$, C_{BW} , C_{WW}). Specifically, two new extra operators O_{G+} and O_{G-} , which contribute to the neutral triple gauge vertices (nTGVs) with a leading energy dependency, are described by novel gauge-invariant SMEFT formulation detailed in Section 2.3.2. Furthermore, this formulation allows for a comprehensive investigation of the $Z\gamma$ vertex, marked by the first application of this fully gauge-invariant method. These achievements not only provide clearer insights into the electroweak interactions but also open up new avenues for exploring BSM phenomena through precisely constrained nTGC parameters.

6.2 Data and Monte Carlo samples

The analysis discussed in this chapter utilizes proton-proton collision data from ATLAS experiment at a center-of-mass energy of $\sqrt{s} = 13$ TeV from 2015 to 2018. The dataset of an integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1[55]}$ and was carefully selected using the ATLAS Good-Run-List (GRL) to ensure the integrity of all relevant detector components. The increase in integrated luminosity from 139 fb^{-1} to 140.1 fb^{-1} and the decrease in uncertainty from 1.7% to 0.83% for the ATLAS detector at the LHC during Run2 were driven by refined measurement techniques and improved calibration. These enhancements were facilitated through precise van der Meer beam separation scans and effective extrapolation to the physics data-taking regime using data from several luminosity-sensitive detectors. The total luminosity used for physics is $140.1 \text{ fb}^{-1[55]}$, divided annually as follow:

- 2015: 3244.5 pb^{-1}
- 2016: 33402.2 pb^{-1}
- 2017: 44630.6 pb^{-1}
- 2018: 58791.6 pb^{-1}

Monte Carlo (MC) event samples are utilized to model EFT nTGC, SM $Z\gamma$, and other non- $Z\gamma$ processes. These samples are processed using the GEANT4^[194] framework with

HIGG1D2^[195] derivation as discussed in Section 5.2. Additional, the HGamGamStar^[196] framework was employed, which is developed upon the HGamCore^[197] framework. The EFT-fun^[198] fitting framework was applied to establish both one-dimensional (1D) and two-dimensional (2D) constraints for nTGC parameters, allowing for the definition of contour plots derived for pairs of parameters.

6.2.1 Simulation of Signal Datasets

In this analysis, the signal samples are systematically divided into two main categories to study $Z\gamma$ production: SM $Z\gamma$ samples and Effective Field Theory (EFT) nTGC $Z\gamma$ samples.

SM $Z\gamma$ samples These samples are generated using SHERPA 2.2.11 event generator as detailed in Section 5.2. The matrix element calculation includes up to one additional parton at Next-to-Leading Order (NLO) and extends to include up for four partons at Leading Order (LO) using the MEPS@NLO. The parton shower settings, which are optimized using the NNPDF3.0nnlo parton distribution function (PDF), incorporate specific parton shower parameters

Additionally, an alternative signal sample was produced using the MADGRAPH_AMC@NLO 2.3.3 event generator with one extra parton at NLO in the matrix element. This uses the NNPDF30_nlo_as_0118 PDF set and employs same isolation cut as the SHERPA samples, ensuring the compatibility and comparability between the two sets of samples.

EFT nTGC $Z\gamma$ samples These EFT samples are generated through a combination of MADGRAPH and PYTHIA8, focusing on probing the effects of six dimension-8 operators with no extra partons in the Leading Order (LO) at the matrix element calculations. They utilize the NNPDF3.0_lo_as_0118 PDF set and apply a more stringent criterion for p_T^γ which exceed 150 GeV. The EFT samples are categorized into one-dimensional (1D) and two-dimensional (2D) analyses to systematically explore nTGCs. The 1D samples examine the impact of individual dimension-8 operators, while the 2D samples enhance the understanding by exploring correlations between pairs of operators.

Each category targets on distinct physical phenomena, employing comprehensive simulation tools to accurately model $Z\gamma$ production for both SM precise measurements and EFT interpretation scenarios. This approach allows for precise comparative studies and deeper

insights into potential new physics signals through higher-dimensional operators.

6.2.2 Simulation of Background Datasets

The quantification of background processes is meticulously executed to ensure the accuracy of the analysis. The background processes considered in this analysis have been simulated with a suite of advanced Monte Carlo generators, including primary Z +jets background and notably $t\bar{t}\gamma$ background processes. These processes are discussed carefully in Section ???. Utilizing POWHEGBox and MADGRAPH_AMC@NLO for hard-scattering calculations, further enhanced by PYTHIA 8.186 for parton showering and hadronization with CT10 and NNPDF2.3lo PDF sets.

All MC samples used in this analysis are listed in Table 6–1.

	Process	Generator
Signal	SM $Z\gamma + 0,1j$ @NLO + 2,3,4j@LO	SHERPA 2.2.11
	SM $Z\gamma + 0.1 j$ @NLO	MADGRAPH
	$Z\gamma$ EFT @ LO - O_{G+} $Z\gamma$ EFT @ LO - O_{G-} $Z\gamma$ EFT @ LO - O_{BB} $Z\gamma$ EFT @ LO - $O_{\tilde{B}W}$ $Z\gamma$ EFT @ LO - O_{BW} $Z\gamma$ EFT @ LO - O_{WW}	MADGRAPH + PYTHIA8
	$Z\gamma$ EFT @ LO - (O_{G+}, O_{G-}) $Z\gamma$ EFT @ LO - ($O_{G+}, O_{\tilde{B}W}$) $Z\gamma$ EFT @ LO - ($O_{G-}, O_{\tilde{B}W}$)	MADGRAPH + PYTHIA8
Background	Z +jets 0j@NLO	POWHEGBox
	$t\bar{t}\gamma/tW\gamma$ @LO	MADGRAPH_AMC@NLO
	$ZZ \rightarrow \ell\ell\ell\ell/W^\pm Z \rightarrow \ell\ell\ell\nu$	SHERPA 2.2.2
	0,1j @NLO + 2,3j@LO	
	$WZ\gamma/WW\gamma$ 0j@NLO + 1,2j@	SHERPA 2.2.11

Table 6–1 Overview of Monte Carlo Samples used in this analysis. Detailed definitions are also documented in Section 6.6.1.

6.3 Analysis Methodologies

This analysis designates a single signal region to facilitate both precision measurements and EFT fitting. It is crucial to focus on the high p_T region to enhance the sensitivity for detecting nTGCs, pivotal for accurate measurements and advancing the searches beyond the SM.

Before unblinding, pseudo data is constructed and used to obtain unfolded distributions and expected exclusive constraints. This analysis specifically unfolds the distributon of photon transverse momentum (p_T^γ) and then uses it for EFT limit setting.

6.3.1 Object Reconstruction

The criteria ensure the definition of baseline and signal objects are introduced below, aligned with the recommendations from the CP groups. The selected baseline objects are subject to the Overlap Removal procedure, distinguishing them from the signal objects used in the final analysis.

Baseline selections for electron candidate:

- have a $p_T > 25$ GeV
- have a pseudorapidity $|\eta| < 2.47$, but not entering the EM calorimeter transition region ($1.37 < |\eta| < 1.52$)
- have a d_0 significance requirement of $|d_0/\sigma(d_0)| < 5$ with the primary vertex
- have a longitudinal impact parameter requirement of $|z_{0\sin\theta}| < 0.5$ mm
- pass the Medium identification working point
- pass the FCLoose isolation working point

Baseline selections for muon candidate:

- have a $p_T > 25$ GeV
- have a pseudorapidity $|\eta| < 2.5$
- have a d_0 significance requirement of $|d_0/\sigma(d_0)| < 3$ with the primary vertex
- have a longitudinal impact parameter requirement of $|z_{0\sin\theta}| < 0.5$ mm
- pass the Medium identification working point
- pass the PflowLoose_FixedRadIso isolation working point

Baseline selections for photon candidate:

- have a $p_T > 150$ GeV

- have a pseudorapidity $|\eta| < 2.37$, and excluding the region $1.37 < |\eta| < 1.52$
- pass the Loose identification working point

Signal selections for photon candidate:

- have a $p_T > 200$ GeV
- pass the Tight identification working point
- pass the FixedCutLoose isolation criteria ($E_T^{\text{cone20}} < 0.065 p_T^\gamma$ and $p_T^{\text{cone20}}/p_T^\gamma < 0.05$)

Baseline selections for jet candidate:

- have a $p_T > 25$ GeV
- have a pseudorapidity $|\eta| < 4.5$
- reconstructed with the anti- k_t algorithm with a radius parameter of $R = 0.4$
- pass the LooseBad jet cleaning requirements
- pass the Medium working point that jet with a $p_T < 120$ GeV and $|\eta| < 2.5$
- pileup mitigation obtained through the Jet Vertex Tagger (JVT)

The Overlap Removal (OR) algorithm is essential in the ATLAS analyses, designed to correct misidentifications where a single physical object is detected as multiple particle types. This algorithm uses the $\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$ metric, which measures angular separation between objects, to differentiate between distinct objects and detection overlaps. Objects may enter multiple containers simultaneously after event reconstruction. The OR algorithm resolves these ambiguities by applying a sequence of selection criteria, ensuring each object is uniquely categorized for accurate analysis.

- jet is removed if it is found within $\Delta R < 0.4$ of a photon, or within $\Delta R < 0.2$ of an electron
- electron or muon is removed if it is found within $\Delta R < 0.4$ of a jet
- photon is removed if it is found within $\Delta R < 0.4$ of an electron or a muon
- electron is removed again if it is found within $\Delta R < 0.2$ of a muon

6.3.2 Event Selections

The precise measurement of $Z\gamma$ production is conducted within a dedicated phase space so called the Signal Region (SR). This region is essential for both precise measurements and the extraction of EFT constraints for the nTGC parameters. This section introduces the kinematic selections and theoretical considerations designed to enhance the sensitivity to

nTGCs.

The initial step in the event selection process involves the application of lepton triggers, as listed in Table 6–2.

Trigger Type	2015 data taking	2016 - 2018 data taking
Single electron	HLT_e24_lhmedium_L1EM20VH	HLT_e26_lhtight_nod0_ivarloose
	HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
	HLT_e120_lhloose	HLT_e140_lhloose_nod0
Di-electron	HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0
		HLT_2e24_lhvloose_nod0
Single muon	HLT_mu20_iloose_L1MU15	HLT_mu26_ivarmedium
	HLT_mu50	HLT_mu50
Di-muon	HLT_mu18_mu8noL1	HLT_mu22_mu8noL1

Table 6–2 Lepton triggers employed in this analysis at 13 TeV.

Two Opposite Sign Same Flavor leptons are selected based on the transverse momentum criteria, where the leading lepton is required to have p_T greater than 30 GeV and the subleading lepton must exceed 25 GeV. This selection targets high-quality data by focusing on leptons with significant p_T , thereby reducing background contributions from lower resonance. In addition to lepton selection, the signal photon must satisfy the requirement that p_T greater than 200 GeV, elevated from the prior threshold of 30 GeV used in previous analyses^[146,148]. This substantial increase is pivotal for suppressing SM background contributions, which are predominantly prominent in the lower p_T regions, thereby enhancing the sensitivity to nTGCs.

Two critical invariant mass requirements are imposed to further refine the selections:

- **Dilepton system** The invariant mass of the dilepton system is constrained to be within 10 GeV of the Z boson mass ($|m_{\ell\ell} - m_Z| < 10$ GeV). This constraints is crucial for ensuring that the leptons are likely decay products of on-shell Z bosons, essential to isolating events within a specific kinematic region where nTGC contributions are pronounced.
- **Leptons and photon system** The sum of invariant mass of the dilepton system ($m_{\ell\ell}$) and invariant mass of the leptons and photon ($m_{\ell\ell\gamma}$) is required to exceed twice the mass of the Z boson ($m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV), effectively eliminating final state radiation

events and reinforcing the selection of particle interactions.

The theoretical formulation for this analysis has been adapted to focus exclusively on on-shell Z bosons, as specified by the new nTGC formulation^[14]. This adaptation is significant since it simplifies the interaction by reducing the structures to form factors when both gauge bosons are on-shell, thereby streamlining theoretical predictions and experimental verification. The EFT model employed considers only leading-order (LO) effects, and no jets are selected in the final state to avoid potential corrections from higher-order (NLO or beyond). Generally, this selective approach is designed to ensure that any observed advancements in cross sections and differential distributions are attributable coming from nTGCs rather than SM or higher-order corrections. A comprehensive summary of event selections applied in this analysis is outlined in Table 6–3.

Signal Region Definition	
Variables	Cut
N_{lep}	2 signal leptons (OSSF)
Leading lepton	$p_T > 30 \text{ GeV}$
Photon	1 signal photon with $p_T > 200 \text{ GeV}$
Jet	exclusive, $N_{\text{jet}} = 0$
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
$m_{\ell\ell} + m_{\ell\ell\gamma}$	$> 182 \text{ GeV}$

Table 6–3 Summary of event selections applied in the signal region.

6.3.3 Variables

In the $Z\gamma$ production, the choice of the variables p_T^γ and ϕ is strategic and essential in the significant physical implications for EFT interpretations. The transverse momentum of leading photon, p_T^γ , is particularly sensitive to deviations from SM predictions, making it a critical parameters for probing higher-dimensional operators within the SMEFT framework. Moreover, the angular variable ϕ , depicted in Fig. 6–2, captures the essence of interference contributions between SM and pure quadratic nTGC effects.

Two critical variables are focused and measured:

- p_T^γ : The transverse momentum of the leading photon, which is highly sensitive to nTGCs, particularly valuable in high p_T region benefit to EFT interpretations

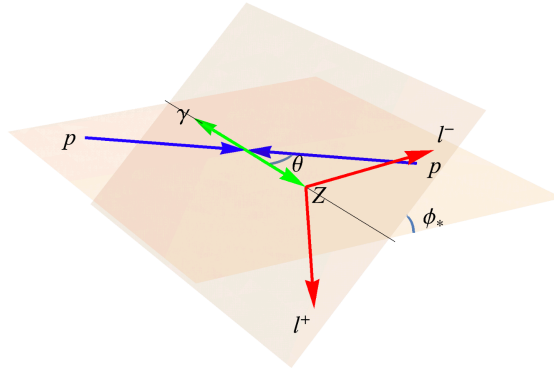


Figure 6–2 Deception of the kinematic configuration for the process $pp \rightarrow Z\gamma$, followed by the leptonic decay $Z \rightarrow \ell^+\ell^-$, as observed in the laboratory frame.

- ϕ : The angle between the scattering plane and the decay plane of the Z boson in the $\ell^+\ell^-$ center-of-mass frame. This angular variable, first introduced in the latest nTGC formulations^[13-14], is crucial as it encapsulates the interference effects between SM and pure quadratic nTGC phenomena

We assume the direction of the quark is along the z-axis, an approximation due to the indeterminate quark direction in collider experiments. The ϕ variable is particularly unique as it is derived from the kinematic orientation of the photon and Z boson decay products, calculated as:

$$\cos \phi = \frac{(\vec{p} \times \vec{Z}) \cdot (\vec{\ell}^+ \times \vec{\ell}^-)}{|\vec{p} \times \vec{Z}| \times |\vec{\ell}^+ \times \vec{\ell}^-|} \quad (6-1)$$

where $\vec{p}$, $\vec{Z}$, $\vec{\ell}^+$ and $\vec{\ell}^-$ represent the momentum vectors of the proton, Z boson, and the decayed leptons, respectively.

6.3.4 Background Estimation

6.3.4.1 Z+jets Estimation

The method for Z+jets background estimation is described in studies involving $Z(\rightarrow \ell^+\ell^-)\gamma$ events, where jet is misidentified as a photon. Building upon the detailed methodology discussed in Section 5.3.4.3, the Z+jets background estimation is refined using the 2D sideband method by categorizing photon events into four distinct regions based on the identification and isolation criteria:

- **Region A: Signal Region** Designed for photons that meet both identification and iso-

lation criteria, focusing on the signal events

- **Region B,C, and D: Control Region** These regions are defined to estimate the background with misidentified jets with different identification and isolation criteria applied.

This method divides both MC simulated samples and actual data events into four distinct regions. The variations between identification and isolation criteria are used to deduce systematic uncertainties. This setup is crucial for incorporating a working point modification by excluding four of the shower shape variables from the Electromagnetic Calorimeter (ECAL) in the Loose ID criteria described in Table 6–4.

Estimation Strategy In this analysis, due to the small fiducial phase space compared to previous $Z\gamma$ measurements^[146,148] at the LHC, a large bin method is utilized to enhance statistical robustness. Typically, the estimation procedure can be divided into the calculation of correlation factor R , purity P , and Z +jets estimation. To overcome the poor statistics, a single wide bin has been employed and kept until the calculation of purity.

- **Correlation Factor R** This factor quantifies correlations between different regions using Z +jets events from MC simulated samples.

$$R = \frac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}} \quad (6-2)$$

where N_X^{Z+jets} represents the number of Z +jets events in region X , $X = A, B, C, D$ from the MC simulations

- **Signal Leakage Parameter** These parameters estimates the signal leakage into different regions, calculated based on the proportion of $Z\gamma$ events in each region from MC simulation.

$$c_B = \frac{N_B^{sig}}{N_A^{sig}}, c_C = \frac{N_C^{sig}}{N_A^{sig}}, c_D = \frac{N_D^{sig}}{N_A^{sig}} \quad (6-3)$$

with N_X^{sig} denotes the number of $Z\gamma$ events in region X , $X = B, C, D$ from the SM $Z\gamma$ MC simulation.

- **Purity P** Purity is defined as the ratio of true signal events to the total number of events, which helps in isolating the signal from background contributions.

$$P = \frac{N_A^{sig}}{N_A^{data} - N_A^{bkg}} \quad (6-4)$$

Category	Description	Shower Shape	LoosePrime4	Tight
Acceptance	$ \eta < 2.37, 1.37 < \eta < 1.52$ excluded	-	✓	✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the ranges $ \eta < 0.8$ and $ \eta > 1.37$)	R_{had1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio between the sum $E_{3 \times 7}^{S2}$ of the energies of the cells contained in a 3×7 $\eta \times \phi$ rectangle (measured in cell units), and the sum $E_{7 \times 7}^{S2}$ of the cell energies in a 7×7 rectangle, both centered around the cluster seed	R_η	✓	✓
	Lateral width of the shower in the η direction	$\omega_{\eta 2}$	✓	✓
	Ratio between the sum $E_{3 \times 3}^{S2}$ of the energies of the cells contained in a 3×3 $\eta \times \phi$ rectangle (measured in cell units), and the sum $E_{3 \times 7}^{S2}$ of the cell energies in a 3×7 rectangle, both centered around the cluster seed	R_ϕ	✓	✓
EM Strip layer	Lateral shower width for maximum strip and two neighbors	ω_{s3}		✓
	Total lateral shower width	ω_{tot}	✓	✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	Difference between the energy of the strip associated with the second maximum in the strip layer, and the energy reconstructed in the strip with the minimal value found between the first and second maximum	ΔE_s		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Table 6–4 Discriminatory variables employed in the LoosePrime4 and Tight ID criteria for photon identification, and the specific cuts associated with energy deposition in the second layer of the calorimeter, denoted by E^{S2} .

- **Estimation of Z+jets** The final step, calculates the number of background events in the signal region, factoring the computed purity and total events

$$N^{Z+jets} = (N_A^{\text{data}} - N_A^{\text{bkg}}) \times (1 - P) \quad (6-5)$$

This four steps method allows for a robust estimation of the Z+jets background while ensuring the integrity of the signal detection process. Building on previous $Z\gamma$ analyses^[146,148], this study shares identical background sources, and same method for background estimation is employed. Here we just briefly reintroduce it here for a streamlined estimation procedure.

Criteria	LoosePrime4, $E_{\text{gap}} = 2 \text{ GeV}$
R	$1.92 \pm 1.09(\text{stat.}) \pm 0.87(\text{syst.})$
P	$0.76 \pm 0.12(\text{stat.}) \pm 0.12(\text{syst.})$
$c_B(\times 10^{-3})$	$1.30 \pm 0.39(\text{stat.}) \pm 2.92(\text{syst.})$
$c_C(\times 10^{-3})$	$33.23 \pm 2.73(\text{stat.}) \pm 0.69(\text{syst.})$
$c_D(\times 10^{-3})$	$0.23 \pm 0.18(\text{stat.}) \pm 0.25(\text{syst.})$
$N_A^{\text{data}} - N_A^{\text{bkg}}$	$341.35 \pm 18.52(\text{stat.}) \pm 0.40(\text{syst.})$
$N_B^{\text{data}} - N_B^{\text{bkg}}$	$2.87 \pm 1.73(\text{stat.}) \pm 0.04(\text{syst.})$
$N_C^{\text{data}} - N_C^{\text{bkg}}$	$57.10 \pm 7.56(\text{stat.}) \pm 0.06(\text{syst.})$
$N_D^{\text{data}} - N_D^{\text{bkg}}$	$2.96 \pm 1.73(\text{stat.}) \pm 0.01(\text{syst.})$

Table 6–5 Parameter utilized in the ABCD method, encompassing choices in identification and isolation gap, and varying generator sources. These parameters are foundational in addressing systematic across different scenarios.

The parameters that enter the ABCD method are detailed in Table 6–5, and the results for the Z+jets study are summarized in Table 6–6.

6.3.4.2 Pile-up Photon Estimation

Pile-up events where photons and leptons arise from separate pp collisions within the same bunch crossing. The positions are initially estimated using a weighted average of calorimeter signals and refined by assessing the longitudinal displacement $\Delta z = z_\gamma - z_{\text{vtx}}$, as detailed in previous discussions in Section 5.3.4.3. z_γ is the photon position and z_{vtx} is the primary vertex position as illustrated in Fig. 6–3

Follow the same estimation strategy, the pile-up contribution is directly estimated from the data by selecting events from the Final State Radiation (FSR) region. The cut on the

Sources	$(ee + \mu\mu) N_{Z+\text{jets}} = 81.90$
Statistical	41.72 (50.94%)
Background	41.48 (50.65%)
Generator	40.58 (49.55%)
E_{gap}	41.47 (50.63%)
Anti-Tight	41.47 (50.63%)
Total	92.45 (112.88%)

Table 6–6 Systematic uncertainties and their impact on Z+jets yields estimated using the data-driven method.

This table lists the estimated yields in the first column, followed by columns detailing the number of uncertainties for each source and their respective contributions as percentages of the estimated yields.

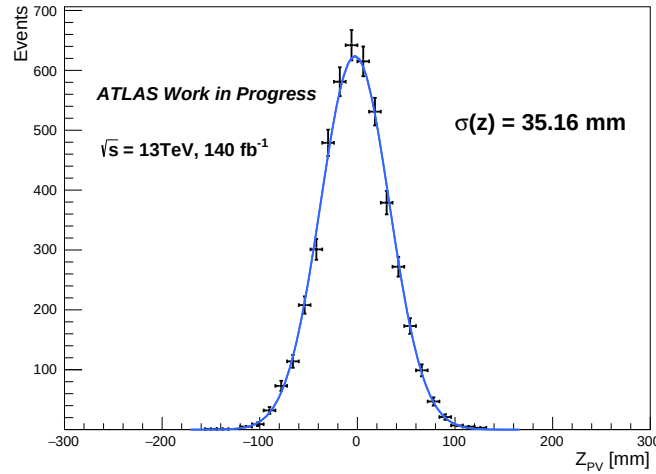


Figure 6–3 Distribution of the primary vertex z for data, the blue line represents the fit to the data.

invariant mass is reversed to $82 \text{ GeV} < m_{\ell\ell\gamma} < 102 \text{ GeV}$ to ensure the three-body system is compatible with the Z boson mass and comes from the same interaction vertex. The contribution from pileup photon background is estimated negligible and less than 0.3% of the total SM predictions.

6.3.4.3 Other Background Estimation

The background processes from $t\bar{t}\gamma$ and multi-boson events, where leptons are misidentified as photon, are estimated using MC simulations. For $t\bar{t}\gamma$ background, where photons and leptons originate from top quark decays, the background is reduced by ensuring the invariant

mass of the lepton pair close to the Z boson mass.

6.3.4.4 Validation Region

The validation region is a critical component of the analysis designed to ensure the reliability and accuracy of MC simulations used in the background estimation. The primary motivation is to verify that the MC simulations replicate the experimental conditions and observed data, particularly in how to model background contributions which are integrated to the overall analysis.

Validation Region Definition	
Variables	Cut
N_{lep}	2 signal leptons (OSSF)
Leading lepton	$p_T > 30 \text{ GeV}$
Photon	1 signal photon with $p_T > 200 \text{ GeV}$
Jet	$N_{\text{jet}} \geq 0$
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
$m_{\ell\ell} + m_{\ell\ell\gamma}$	$> 182 \text{ GeV}$

Table 6–7 Summary of event selections applied in the validation region. Number of jet selection is inversed in this region to require at least 1 selected jet for each event candidate.

The validation region is defined by selecting events that include a lepton pair with opposite sign and same flavor, one signal photon with $p_T^\gamma > 200 \text{ GeV}$, but required to have at least one jet. This selection criteria summarized in Table 6–7 closely mirrors those of the signal region to ensure that the validation process is directly relevant to the conditions under which the actual signal is evaluated.

By comparing the data derived from this region with the predictions from MC simulations, as depicted in Fig. 6–4, it is possible to assess the consistency and accuracy of the simulation as well as background estimation. The comparison, focuses on statistic uncertainty to isolate discrepancies or confirmations between the observed data and the model predictions. This validation region provides a robust framework to confirm the reliability of data-driven methods used in this analysis, ensuring that the MC models are well-tuned to the experimental realities and thereby enhancing the confidence in the final analysis results.

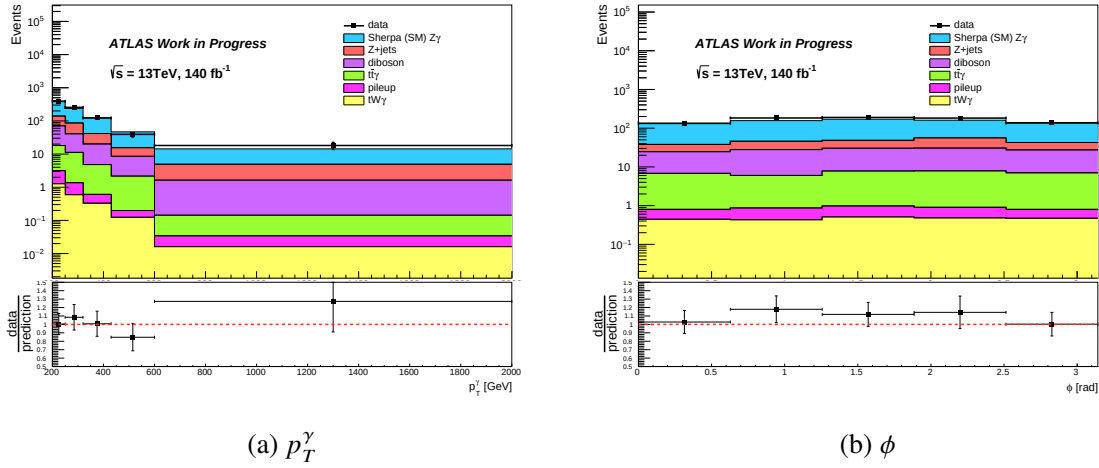


Figure 6–4 Comparison for Data vs MC in this validation region.

6.4 Systematic Uncertainties

The assessment of systematic uncertainties is integral to refine the accuracy of the measurements obtained from the ATLAS detector and encompasses both experimental and theoretical components. This section delves into the experimental systematic uncertainties, which arise due to the finite resolution of object reconstruction and the modelling processes during the simulations.

6.4.1 Experimental Uncertainties

Experimental systematic uncertainties arise from the limitations in the resolution of reconstructed objects by the ATLAS detector and the corresponding simulations. All these uncertainties are necessary for robust exploration into EFT fits, which impact the accuracy of measurements involving electrons, muons, photons and are estimated by varying around nominal value ($\pm 1\sigma$).

Electrons and Photons Uncertainties arise primarily from variations in energy scale and resolution. For electrons, systematic uncertainties come from identification, isolation, and trigger efficiency are considered. The reconstruction and isolation efficiencies for photons are also considered.

Muons Uncertainties mainly come from variations in momentum resolution, the smearing of identification, and muon spectrometer (MS) tracks are included.

Jets Uncertainties related to jet energy scale (JES) and resolution (JER) with different choice of NP value, using the FullJER Category Reduction (R4_CategoryReducton_FullJER) are utilized. These uncertainties integrates considerations of detector modelling, statistical effects, flavor composition^[199], and the description of pileup jets.

Each category of uncertainties is discussed detailed in Section 5.4.1 and addressed through the adjustment in scale factors.

6.4.2 Theoretical Uncertainties

Theoretical uncertainties impact the precision of signal predictions due to missing higher-order corrections in cross section calculations, as discussed in Section 5.4.2. These uncertainties are primarily derived from variations in the renormalization (μ_r) and factorization (μ_f) factors.

Scale Variation Addressed by varying the renormalization (μ_r) and factorization (μ_f) factors, which are critical for determining the cross section.

Specific Configuration for SHERPA 2.2.11 SM $Z\gamma$ MC samples:

- ME_ONLY_MUR0.5_MUR0.5_PDF303200_PSMUR0.5_PSMUF0.5
- ME_ONLY_MUR0.5_MUF1_PDF303200_PSMUR0.5_PSMUF1
- ME_ONLY_MUR1_MUF0.5_PDF303200_PSMUR1_PSMUF0.5
- ME_ONLY_MUR1_MUF1_PDF303200_PSMUR1_PSMUF1
- ME_ONLY_MUR2_MUF1_PDF303200_PSMUR2_PSMUF1
- ME_ONLY_MUR1_MUF2_PDF303200_PSMUR1_PSMUF2

Specific Configuration for MADGRAPH EFT MC samples:

- MUR0.5_MUF0.5_PDF315000
- MUR0.5_MUF1.0_PDF315000
- MUR1.0_MUF0.5_PDF315000
- MUR1.0_MUF2.0_PDF315000
- MUR2.0_MUF1.0_PDF315000
- MUR2.0_MUF2.0_PDF315000

PDF Variation The accuracy of theoretical cross section calculation is influenced by the choice of Parton Distribution Function (PDF) sets. Uncertainties in these calculation are assessed using the NNPDF error set. This estimation involves using weights from MC samples to normalize variations and align with truth cross section, thereby minimizing the double counting of uncertainties. To estimate the uncertainty in the PDF sets, we employ the standard deviation method^[200] as recommended by the Physics Modelling Group (PMG), calculated using the formula:

$$\Delta X = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - X_0)^2} \quad (6-6)$$

where ΔX represents the uncertainty, N is the number of PDF sets which depends on the choice of event generator, and X_i are the varied values.

α_s Uncertainty Uncertainties related to the strong coupling constant (α_s) are evaluated by adopting the same PDF set with two distinct α_s values. Specifically, the NNPDF30_nlo_as_0119 and NNPDF30_nlo_as_0117 sets are used for the Next-to-Next-to-Leading Order (NNLO) calculations. The α_s uncertainty is quantified as:

$$\delta\alpha_s = \frac{\sigma(\alpha_s^{\text{down}}) - \sigma(\alpha_s^{\text{up}})}{2} \quad (6-7)$$

where $\sigma(\alpha_s^{\text{up/down}})$ refers to the cross section calculations using the lower and upper α_s values, respectively.

Electroweak Correction The electroweak (EWK) corrections^[201] are incorporated into the MC simulations using dedicated weights. These corrections are based on the electroweak virtual approximation and are varied within the sample to estimate the impact. Specific configurations used for evaluating EWK corrections include:

- ME_ONLY_MUR1_MUF1_PDF303200_ASSEW
- ME_ONLY_MUR1_MUF1_PDF303200_MULTIASSEW
- ME_ONLY_MUR1_MUF1_PDF303200_EXPASSEW

Parton Shower Uncertainty For the Parton Shower (PS) uncertainty^[201], which obtained alongside the scale variations, following the recommendation described in PMG System-

atic Recipes^[201]. The uncertainty related to the PS is quantified by adjusting the scales in a correlated way in the Matrix Element and Parton Shower for merged predictions.

6.4.3 Generator Uncertainties

Generator systematic uncertainties arise from differences in different generators, such as SHERPA and MADGRAPH. In the estimation of generator uncertainty, both SHERPA 2.2.11 and MADGRAPH are employed to simulate SM $Z\gamma$ process, and the discrepancies are extracted and assigned as the uncertainty. The impact on the accuracy and reliability of the simulation results, is necessary to achieve a more accurate and dedicated estimations.

6.4.4 Background Uncertainties

The Z+jets background estimation employs a data-driven method that accounts for both statistical and systematic uncertainties arising from several sources, including luminosity, object reconstruction, and modelling. In this analysis, further uncertainties derived from different generator choices, such as SHERPA 2.2.11 and MADGRAPH, which impact signal leakage parameters and the overall Z+jets estimation. Variations on the correlation factor R are due to the selection of anti-tight identification criteria and isolation gap values. Specifically, uncertainties for the identification criteria are assessed by comparing different definitions (LoosePrime3, LoosePrime4, and LoosePrime5), and for the isolation gap, by adjusting the gap value from 1 GeV to 3 GeV.

6.4.5 Other Uncertainties

Luminosity A 0.83 % uncertainty^[55] is incorporated as the luminosity uncertainty. The decreased uncertainty from 1.7% to 0.83%, compared with previous chapter, enhances the precision of the luminosity measurement and improves the accuracy of cross section measurement.

Pileup Reweighting Additional systematic uncertainties from pileup reweighting are addressed by varying the parameter $\langle\mu\rangle$ (the actual number of proton-proton collision) using PRW_DATASF__1up and PRW_DATASF__1down in the reweighting process, ensuring accurate compensation for variations in collision counts.

6.4.6 Impact of Systematic Uncertainties

Systematic uncertainties are incorporated into the unfolded results by using different input variations for the unfolding and migration matrices, which include adjustments in kinematics or weights. Statistical uncertainty is calculated using pseudo data, generated to fluctuate around the nominal bin value, with the difference serving as the error. The differences between these varied results and the nominal case determine the systematic uncertainty. Fig. 6–5 details the distribution of these systematic uncertainties across various kinematic variables.

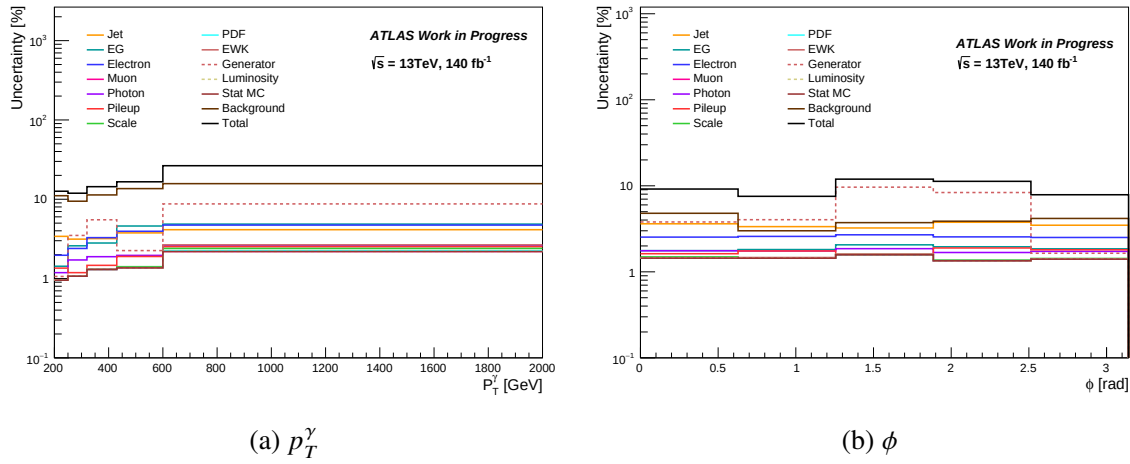


Figure 6–5 Breakdown of systematic uncertainties as function of p_T^γ and ϕ , presented as percentages relative to the SM $Z\gamma$ events. The uncertainties illustrated here have been calculated following the propagation through the VIPUnfolding framework and are factored into the final measurements.

6.5 Measurements

The measurements and the unfolded distributions are used to interpret the experimental data within the SMEFT framework. Unfolding is confined to specific regions, allowing for a direct and model independent comparison between experimental results and theoretical predictions, as well as correcting detector response in data. This method is critical for rigorously testing the SM and probing for new physics through EFT, effectively linking theoretical insights with precise experimental observations.

6.5.1 Definition of Fiducial Region

In this specific region, only stable particles with a mean lifetime $c\tau$ exceed 10 mm are considered. We primarily focus on "prompt" leptons (electrons and muons) and photons, which emerge directly from high-energy collision events, thereby furnishing insights into the fundamental mechanisms of particle interactions and decays. Within this framework, photons are described as "dressed", which entails the adjustment of the momentum by the inclusion of the momentum of nearby photons within a ΔR less than 0.1.

Leptons selected for analysis must satisfy the transverse momentum p_T threshold, as well as leptons. Furthermore, the pseudorapidity (η) for both electrons and muons is constrained to be less than 2.47, ensuring that detector inefficiencies related to geometirc discontinuities do not affect the accuracy at the truth level. Photons are required to have a transverse momentum greater than 150 GeV and a pseudorapidity ($|\eta|$) less than 2.37. Additionally, photons must also pass isolation criteria, which ensuring that the scalar sum of the transverse energies of all surrounding particles (excluding muons and neutrinos) within a ΔR of 0.2 does not exceed 7% of the photon transverse energy. Jets are defined with specific requirements for acceptance: a transverse momentum greater than 30 GeV for central jets ($|\eta| < 2.5$) and more than 50 GeV for forward jets ($2.5 < |\eta| < 4.5$). Moreover, any jet fails within a ΔR of 0.4 of a photon are excluded.

Dressed electrons, muons, photons, and jets are required to adhere to the kinematic criteria described in Section 6.3.1. This compliance ensures that all particles considered are subject to high standards of measurement precision and reliability, thus bolstering the effectiveness of the subsequent data interpretation and analysis. All selections are listed in Table 6–8, and remain the same with the selections defined in signal region as much as possible.

Quantity	Cuts
lepton cuts	$p_T^{\ell_1} > 30 \text{ GeV}, p_T^{\ell_2} > 25 \text{ GeV}, \eta < 2.47$
photon cuts	$p_T^\gamma > \mathbf{200 \text{ GeV}}, \eta < 2.37, \Delta(\gamma, \ell) > 0.4$
photon isolation	$E_T^{\text{cone20}}/E_T^\gamma < 0.07$
jet cuts	$p_T > 30 \text{ GeV}$ if $ \eta < 2.5$ $p_T > 50 \text{ GeV}$ if $2.5 < \eta < 4.5$
mass cuts	$ \mathbf{m}_{\ell\ell} - \mathbf{m}_Z < \mathbf{10 \text{ GeV}}, (m_{\ell\ell} + m_{\ell\ell\gamma}) > 182 \text{ GeV}$
other cuts	$\mathbf{N_j = 0}$

Table 6–8 Selections employed to define this fiducial region.

6.5.2 Fiducial Cross Section

The fiducial cross section is quantified with the dedicated fiducial phase space, as specified in Table 6–8. The computation is conducted using the following equation:

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times L} \quad (6-8)$$

where N_{obs} denotes the number of events observed that pass the selection criteria, N_{bkg} represents the expected number of background events, and L denotes the integrated luminosity of the analyzed dataset. The correction factor, C , is employed to compensate for inefficiencies and limitations in the detector capability for a more accurate measurement.

The correction factor C is calculated from the SHERPA 2.2.11 MC simulations tailored for $Z\gamma$ signal sample, and defined as:

$$C = \frac{N_{\text{reco}}}{N_{\text{fid}}} \quad (6-9)$$

Here, N_{reco} refers to the number of reconstructed events that successfully pass the signal region selection, whereas N_{fid} accounts for the number of truth-level events that employ with the fiducial region criteria. The implementation of this correction factor is crucial for adjusting the measured distribution to accurately reflect detector effects.

The inclusive correction factor C , considered both the electron and muon channels, has been precisely estimated to be $C = 0.563 \pm 0.006$ (stat.). This adjustment ensures that the derived measurements accurately depict the actual particle interactions, thereby minimizing any distortions caused by the detection process.

6.5.3 Unfolding

The unfolding procedure^[202] detailed in Section 5.5.3.3 is structured as a robust method to transition from detector-level observations to particle-level distributions, ensuring comparability with theoretical predictions and other experiments. This process, essential for interpreting high energy physics data, comprises several steps:

Selection of Unfolding Method The Iterative Bayesian Unfolding (IBU)^[203] method is chosen for its efficiency, utilizes the SHERPA 2.2.11 MC simulation of SM $Z\gamma$ samples. The methodology is tailored to accurately reconstruct the truth particle distributions from the observed data.

Determination Number of Iterations The determination of the number of iterations used in Bayesian Unfolding is a critical component of the unfolding procedure, optimized to balance the bias and statistical uncertainty inherent in the procedure. A detailed explanation is given below, of how the optimal number of iterations is determined:

- **Generation of Pseudo Data** Initially, ten thousand pseudo experiments, termed "toys", are generated. This involves fluctuating the truth level distribution of the MC simulated signal for each bin using a Gaussian distribution with mean zero and a standard deviation determined by $\sigma = \sqrt{N_{\text{truth}}^{\text{bin}}}$. Each fluctuated distribution is then processed through the unfolding procedure using the nominal detector response, yielding datasets referred to as "reco toys".
- **Unfolding of Reco Toys** These reco toys are subsequently unfolded using the Bayesian method with varying number of iterations to study the impact of iteration on the final results. Each unfolded dataset is named as "unfolded toys".
- **Calculation of Bias** Bias for each bin is calculated as the difference ratio between the bin contents of the unfolded toys and the truth toys, defined as:

$$\text{Bias}_{\text{bin}} = \frac{\text{unfold toy}_{\text{bin}} - \text{truth toy}_{\text{bin}}}{\text{truth toy}_{\text{bin}}} \quad (6-10)$$

This bias metric provides a quantitative measure of how the number of iterations affects the accuracy of unfolded results, with a trend observed of decreasing bias with an increasing number of iterations.

- **Estimation of Statistical Uncertainty** To assess the impact of iteration count on statistical uncertainty, an additional ten thousand bootstrap toys are unfolded for each iteration count. The Root Mean Square (RMS) of the unfolded bin contents across these toys is computed, and the relative statistical uncertainty is estimated by dividing the RMS value by the nominal unfolded content of each bin, as illustrated in Fig. 6-6 as function of p_T^γ .
- **Overall Uncertainty Assessment** The overall uncertainty is then calculated for each bin by combining both bias and relative statistical uncertainty:

$$\text{total} = \sqrt{\text{bias}^2 + \text{stat}^2} \quad (6-11)$$

This provides a comprehensive view of the total uncertainty involved in the unfolding process, facilitating a combined assessment of both bias and statistical error, as shown

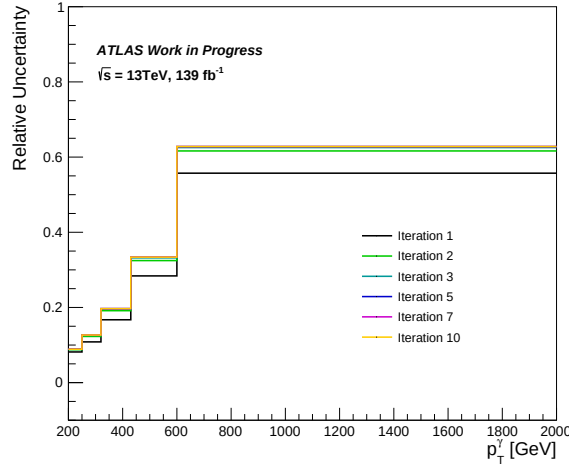


Figure 6–6 Relative statistical uncertainties from different iterations, this figure demonstrates that the increase of iterations numbers leads to greater statistical uncertainties.

in Fig. 6–7.

- **Optimization and Selection of Iterations** After analyzing both bias and statistical uncertainties for different iteration numbers, a two iteration approach is determined to be optimal. This decision is based on achieving the best compromise between minimizing the bias and controlling the statistical uncertainties, thereby ensuring reliable and accurate unfolding results. This optimized unfolding procedure, using two iterations with the Bayesian method, is then adopted as the nominal technique for unfolding the data.

This systematic and detailed approach ensures that the unfolding procedure robustly quantifies and minimizes uncertainties, leading to precise and trustworthy results in high-energy physics analyses.

Calculation of Correction Factors

- **Fiducial Correction** Defined for events that are reconstructed within the signal region at the reconstructed level but do not reside within the fiducial region, and can be expressed as:

$$C_{\text{fid},i} = \frac{N_i^{\text{SR\&FR}}}{N_i^{\text{FR}}} \quad (6-12)$$

- **Efficiency Correction** Accounts for events that enter the fiducial region but are not

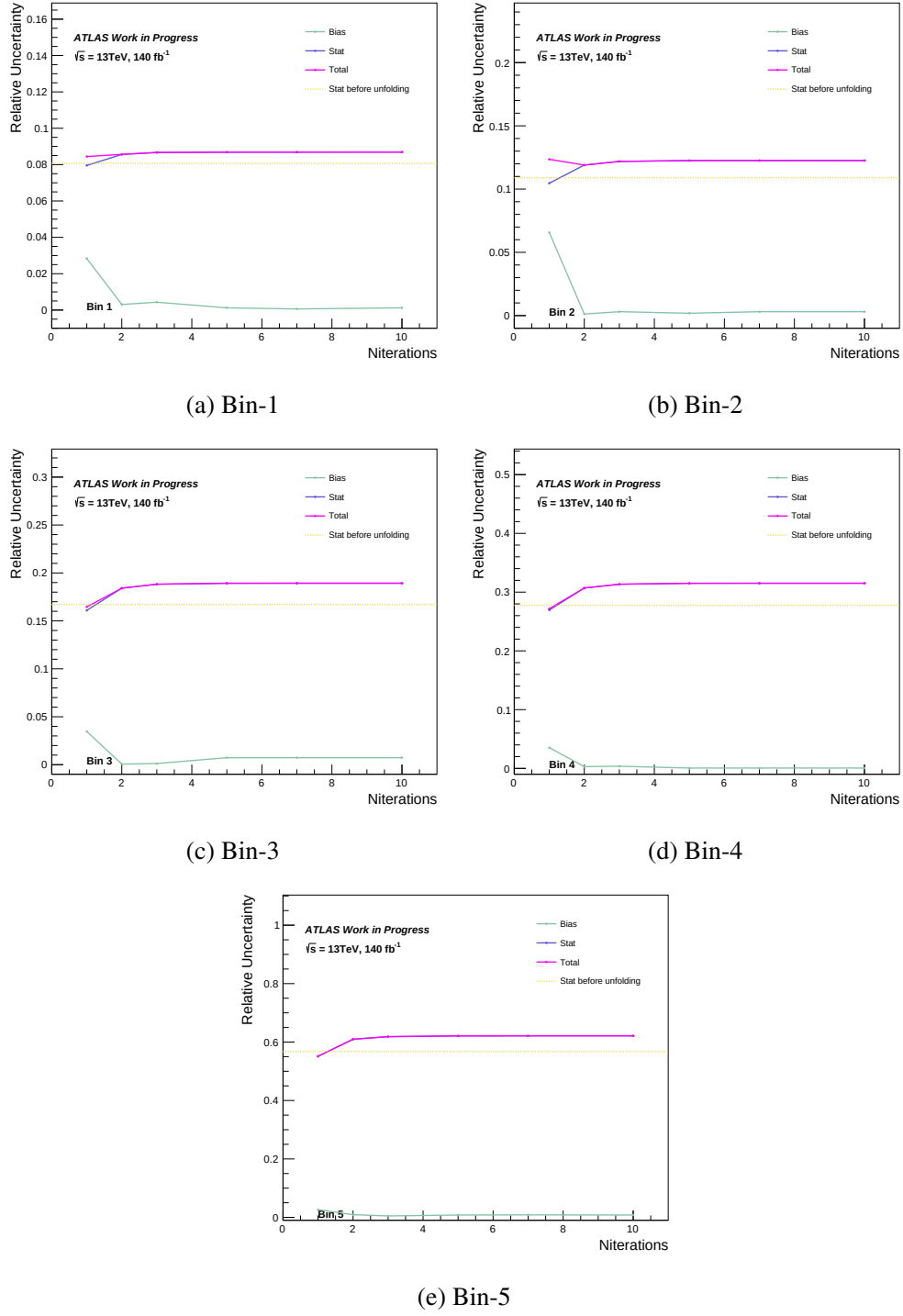


Figure 6–7 Unfolding bias and relative statistical uncertainty with different iteration numbers in bins of p_T^γ distribution. "Total" denotes the combined uncertainty, determined by taking the square root of the sum of squares of these two components.

reconstructed in the signal region, defined as:

$$\epsilon_{\text{cor},i} = \frac{N_i^{\text{SR\&FR}}}{N_i^{\text{SR}}} \quad (6-13)$$

These corrections are integral to the analysis as they enhance the accuracy of the event classification by compensating for the discrepancies caused by the imperfect reconstruction capabilities of the detector, as shown in Fig. 6–8, thereby aligning the reconstructed data more closely with the true physical phenomena being studied.

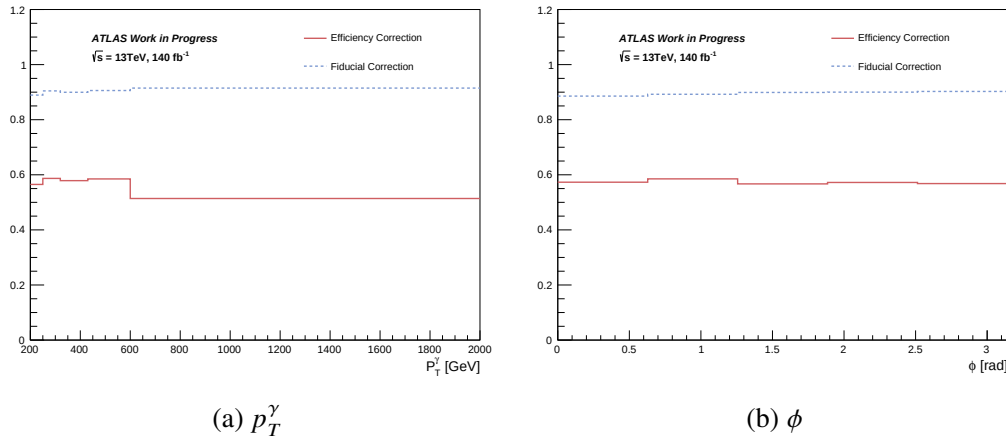


Figure 6–8 Fiducial and efficiency corrections as function of the p_T^γ and ϕ variables utilized in the unfolding procedure.

Utilizing of Migration Matrices Migration matrices are employed to correct for the migration of event counts between bins in the variable of interest due to the detector resolution and efficiency. These matrices, depicted in Fig. 6–9 are fundamental for transferring information about how events at the detector level correlate with the truth level, thus supporting the accurate reconstruction of physical distributions.

Statistical Uncertainty Management Statistical uncertainties are managed by performing Monte Carlo simulations. One thousand pseudo-experiments are conducted, each fluctuating the observed bins according to a Poisson distribution, followed by repeating the unfolding for each pseudo-experiment. This step ensures that both signal and background statistical errors are robustly propagated.

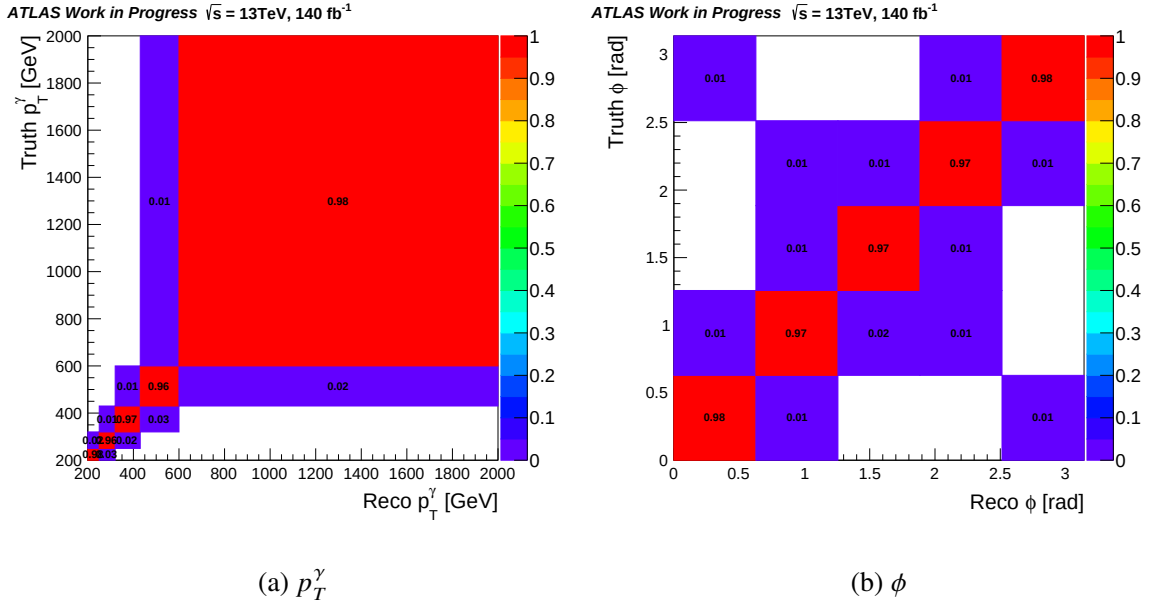


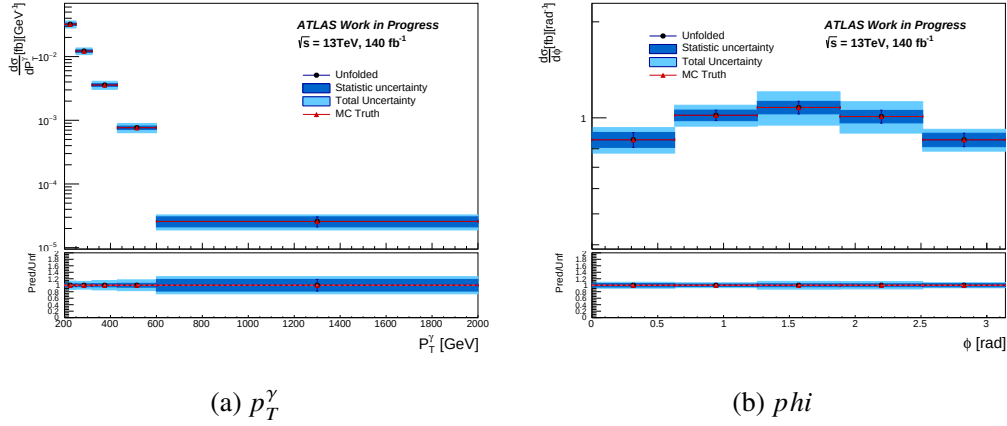
Figure 6-9 Migration matrices for various kinematic variables.

Closure Tests The unfolding closure test is an essential validation method in data analysis that ensures an unfolding algorithm accurately reconstructs truth distributions from the observed data, which includes detector effects. By comparing the ratio of unfolded pseudo data to MC truth predictions and the ratio should be one ideally, which checks the reliability of the algorithm to effectively reverse detector distortions, as depicted in Fig. 6-10. A successful test confirms the reliability of the unfolding method by observing the good agreements, essential before the application to actual experimental data. It also helps optimize algorithm parameters and quantify potential errors, and playing a crucial role in substantiating the scientific accuracy of the analysis.

6.5.4 Results

The estimated yields for various MC simulated processes are summarized in Table 6-9 in the signal region for electron and muon channels, detailing statistical and systematic uncertainties.

The analysis incorporates a Leading-Order (LO) comparison, primarily tailored for unfolding distributions to facilitate EFT fitting, where the nTGC formulation is inherently constructed at LO. This strategic alignment ensures that the theoretical and analytical approaches are harmoniously applied, enhancing the accuracy and relevance of EFT parameter estima-

**Figure 6–10 Unfolding closure test.**

The lower panel displays the ratio of the unfolded pseudo data to the predicted MC truth values, with the light blue band representing the total uncertainty.

Source	$ee + \mu\mu$
SM $Z\gamma$	$271.0 \pm 2.4(\text{stat.}) \pm 44.3(\text{syst.})$
Z+jets	$81.9 \pm 41.7(\text{stat.}) \pm 82.5(\text{syst.})$
diboson	$33.5 \pm 4.6(\text{stat.}) \pm 10.0(\text{syst.})$
pileup	$1.0 \pm 0.1(\text{stat.}) \pm 0.2(\text{syst.})$
$t\bar{t}\gamma$	$0.3 \pm 0.2(\text{stat.}) \pm 0.1(\text{syst.})$
$tW\gamma$	$0.1 \pm 0.0(\text{stat.}) \pm 0.0(\text{syst.})$
Total	$387.8 \pm 42.0(\text{stat.}) \pm 91.2(\text{syst.})$

Table 6–9 Contributions from different processes and associated uncertainties derived from the reconstructed level.

tions.

Utilizing MATRIX^[204–205], a computational framework leveraging the MC integrator MUNICH, the study achieves precise evaluation of differential cross sections up to Next-to-Next-to-Leading Order (NNLO) in QCD. This advanced methodology not only enhances the accuracy of theoretical predictions by including systematic and transverse momentum subtraction techniques but also provides NNLO accuracy to improve modelling.

Practical applications of this framework facilitate direct comparisons between simulated predictions and experimental data. A comparative result shown in Fig. 6–11, using both pseudo data generated from MADGRAPH for the SM $Z\gamma$ process and theoretical predictions.

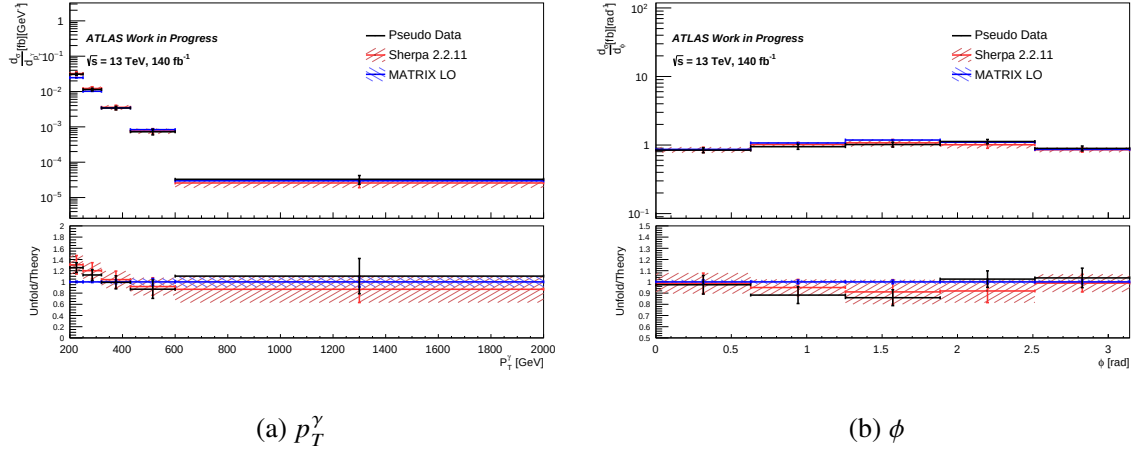


Figure 6–11 Comparison of theoretical predictions.

This figure displays theoretical predictions from SHERPA and MATRIX at LO, alongside pseudo data generated from MADGRAPH, facilitating a direct evaluation of model accuracy and consistency.

These comparisons indicate a reasonable agreement between the unfolded distribution from SHERPA 2.2.11 and the fixed-order calculations provided by MATRIX, reinforcing the applicability of the theoretical frameworks employed.

6.6 EFT Interpretation

This section discusses the evaluation of electroweak interactions in the SMEFT focusing on the $SU(2) \times U(1)$ structure of gauge boson couplings. It highlights that any deviation from the SM predictions could be the sign of new physics, and providing tests at the LHC for evidence of $ZZ\gamma$ or $\gamma Z\gamma$ couplings, which are forbidden at the SM tree level. Unfolded distribution of leading photon transverse momentum p_T is used to set limits within the SMEFT framework, which is particularly sensitive to nTGCs. This approach detects potential enhancements in the high p_T region, which is crucial for probing nTGC contributions. Experimental constraints on dimension-8 nTGC operators are determined and then transformed into bound of form factors from the Effective Vertex Approach, to obtain the first data results with the most up-to-date nTGC formulations.

6.6.1 Fitting Inputs

In this study, the MADGRAPH + PYTHIA8 generators are utilized to simulate EFT nTGC samples, incorporating all relevant interaction terms: pure SM, pure quadratic term, and interference between pure SM and quadratic terms. The simulation involves dynamic adjustments of the Wilson coefficients of dimension-8 operators, facilitated through reweighting cards in MADGRAPH. This methodology allows for parameters to be modified during event generation, enabling a detailed parametric analysis of cross sections at the truth level.

To explore neutral Triple Gauge Couplings (nTGCs) systematically, the analysis implements both one-dimensional (1D) and two-dimensional (2D) EFT samples, as listed in Table 6–1. The 1D analysis focuses on the impact of individual dimension-8 operators by varying one Wilson coefficient at a time. This approach isolates the contributions of simple parameters on the theoretical predictions. Transitioning to a more complex analysis, the 2D approach examines correlations between pairs of dimension-8 operators by simultaneously varying two Wilson coefficients. This dual-parameter exploration significantly enhances the understanding of the interplay between coefficients and their combined influence on nTGC sensitivities.

Parameterizations are employed to represent the cross sections for this analysis. The cross section for the 1D configuration is expressed as a polynomial function:

$$\sigma_{Z\gamma} = \sigma_0 + \sigma_1 C_j + \sigma_2 C_j^2 = \sigma_0 + \tilde{\sigma}_1 [\Lambda_j^{-4}] + \tilde{\sigma}_2 [\Lambda_j^{-8}] \quad (6-14)$$

and for the 2D configuration is described as:

$$\sigma_{Z\gamma} = \sigma_0 + \sigma_1 C_i + \sigma_2 C_j + \sigma_3 C_i^2 + \sigma_4 C_i C_j + \sigma_5 C_j^2 \quad (6-15a)$$

$$= \sigma_0 + \sigma_1 [\Lambda_i^{-4}] + \sigma_2 [\Lambda_j^{-4}] + \sigma_3 [\Lambda_i^{-8}] + \sigma_4 [\Lambda_i^{-4}] [\Lambda_j^{-4}] + \sigma_5 [\Lambda_j^{-8}] \quad (6-15b)$$

where C_i and C_j denote the varied Wilson coefficients of dimension-8 operators, while $[\Lambda_i]$ and $[\Lambda_j]$ represent the new physics energy scales related to nTGCs. Each coefficients σ_i in these parameterization equations captures distinct aspects of the contributions influenced by the dimension-8 operators. The extraction of these coefficients from the fit provides a quantitative basis for adjusting the Wilson coefficients in the SMEFT framework.

The quality of fit to the data is quantified through χ^2 square metrics, confirming a robust fit in the parameterization method employed for EFT extraction. Once the coefficients are

extracted, they are integrated into the EFT fitting procedure to allow extraction of constraints on relevant parameters.

6.6.2 Statistical Model

In this analysis, we employ a robust statistical framework to establish one-dimensional and two-dimensional limits on nTGC parameters within the SMEFT framework. To achieve this, a statistical model integrates Monte Carlo predicted cross sections of the SM along with the interference and quadratic terms for each coupling. For the one-dimensional extraction, a single nTGC parameters is varied while keeping others fixed to zero, and in two-dimensional scenarios, pairs of parameters are varied simultaneously to examine the correlations.

Statistical Model and Fitting The differential cross section model for a given coupling c is expressed as:

$$\frac{d\sigma^i}{dX}(c) = \frac{d\sigma_{\text{SM}}^i}{dX}(1 + \theta) + c \cdot \frac{d\sigma_{\text{int}}^i}{dX} + c^2 \cdot \frac{d\sigma_{\text{qua}}^i}{dX} \quad (6-16)$$

where θ is a nuisance parameter representing the theoretical uncertainty on the SM prediction. This model is fit to the unfolded data using a maximum likelihood method^[206-207], where the likelihood function $\mathcal{L}(c, \hat{\theta})$ is defined as:

$$\mathcal{L}(c, \hat{\theta}) = \frac{1}{\sqrt{(2\pi)^k \cdot |V|}} \exp^{-\frac{1}{2}\chi^2(c, \hat{\theta})} \prod_{\hat{\theta}} G(\hat{\theta}) \quad (6-17)$$

The χ^2 test statistic is employed to measure the agreement between the predictions of the statistical model and the unfolded experimental data, and defined as:

$$\chi^2(c, \hat{\theta}) = [y - f(c, \hat{\theta})]V^{-1}[y - f(c, \hat{\theta})] \quad (6-18)$$

In this expression:

- y represents the vector of unfolded measurements.
- $f(c, \hat{\theta})$ is the model predicted for the parameters c and the vector of nuisance parameters $\hat{\theta}$.
- V^{-1} is the inverse of the covariance matrix V , which accounts for the variances and covariances of the measurements, ensuring that the differences between the model predictions and the actual measurements are properly scaled by their associated uncertainties.

The covariance matrix V is essential as it provides a weighted context for evaluating the residuals (the differences between the observed data and model predictions). By using the inverse of this matrix, each element of the residual vector is appropriately adjusted for the uncertainty and correlation in the data, making the χ^2 a robust measure of model fit.

Profile Likelihood Method The key aspect of our statistical analysis is the use of the profile likelihood method^[208-209]. This approach adjusts the likelihood function to concentrate on the parameter of interest (POI) by holding other parameters at the conditional optimal values. The profile likelihood ratio, a test statistic $q(c)$, is formulated as:

$$q(c) = -2\log\left[\frac{\mathcal{L}(c, \hat{\theta}_c)}{\mathcal{L}(\hat{c}, \hat{\theta})}\right] \quad (6-19)$$

The ratio, where $\mathcal{L}(c, \hat{\theta}_c)$ is the conditional maximum likelihood for a given value of c , and $\mathcal{L}(\hat{c}, \hat{\theta})$ is the unconditional maximum likelihood, follows a χ^2 distribution under the assumptions of Wilk's theorem. This distribution is used to determine the 95% Confidence Intervals for the parameter c .

Application of the 95% Confidence Level (C.L.) The 95% confidence intervals^[210-211] are constructed using the quantiles of the χ^2 distribution. These intervals are calculated by integrating the χ^2 probability density function from zero to a χ^2 value that encompasses 95% of the distribution:

$$\int_0^{q(c)} \chi^2(m=1) dp = 95 \quad (6-20)$$

Here m represents the degrees of freedom, typically equating to the number of parameters estimated simultaneously. This measure provides a statistically valid range within which the true parameter value is expected to lie with 95% certainty.

Application into EFT Models The extracted parameters, along with their respective 95% confidence intervals, are subsequently integrated into the EFT model. This integration updates the theoretical framework with experience-based values, thus enhancing the predictive power of the model and the interpretation of complex particle interactions governed by dimension-8 operators within the SMEFT framework.

This comprehensive statistical methodology establishes a robust exploration of the nTGC parameter space.

6.6.3 Theoretical Formulation

6.6.3.1 Effective Field Theory Approach

The Standard Model Effective Field Theory (SMEFT) is a widely utilized framework for investigating potential new physics phenomena, which extends the Standard Model (SM) by incorporating the higher-dimension operators that account for interactions beyond the SM and not observable at the current energy scales.

The effective Lagrangian for neutral Triple Gauge Couplings (nTGCs) within the SMEFT is given as:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d-4}} O_i^4 \quad (6-21)$$

here, d denotes the dimension of operator O_i^d , and c_i represents the Wilson coefficient associated with each operator. These coefficients are key to understanding the strength and nature of new physics interactions. The parameter, Λ is the mass-dimension scale that corresponds to the energy scale of new physics phenomena potentially integrated in this formulation.

Within the SMEFT, nTGCs are particularly associated with dimension-8 operators. Unlike dimension-6 operators, which do not induce nTGCs, dimension-8 operators such as O_{G+} , O_{G-} , O_{BB} , $O_{\tilde{B}W}$, O_{BW} , and O_{WW} are specifically studied for their potential to reveal new aspects of particle interactions. The coefficients of these operators, expressed as C_{G+}/Λ^4 , C_{G-}/Λ^4 , C_{BB}/Λ^4 , $C_{\tilde{B}W}/\Lambda^4$, C_{BW}/Λ^4 , and C_{WW}/Λ^4 , parameterize the strength of the interactions and are critical for deriving the experimental constraints and theoretical predictions within this extended framework. This approach allows to systematically study and extract limits of the SM and probe signals for new physics that could manifest through interactions described by these higher-dimension operators.

6.6.3.2 Effective Vertex Function Approach

An alternative method employed is the vertex function approach, which provides a refined method for analyzing the interactions with the most general $Z\gamma V^*$ vertex and V represents either Z or γ . The formulation of the vertex function incorporates the complexities of potential new physics interactions beyond the SM.

The anomalous vertex function for the $Z\gamma V^*$ interaction is systematically expressed as:

$$\Gamma_{Z\gamma V^*}^{\alpha\beta\mu(8)}(q_1, q_2, q_3) = \frac{e(q_3^2 - M_V^2)}{M_Z^2} \left[(h_3^V + \frac{h_4^V}{2M_Z^2} q_3^2) q_{2\nu} \epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2} q_2^\alpha q_{3\nu} q_{2\sigma} \epsilon^{\beta\mu\nu\sigma} \right] \quad (6-22)$$

In this equation, q_i denotes the momentum of the gauge bosons involved, and h_i^V are dimensionless coefficients of the Lorentz tensors. The terms h_3^V, h_4^V represent CP-conserving interactions, whereas h_1^V, h_2^V are associated with CP-violating processes. Notably, the relation $h_4^V = 2h_5^V$ simplifies the function, underlining the critical relationship between these coefficients.

The sensitivity of the vertex function to the transverse momentum of leading photon (p_T^γ) is pivotal in deriving the exclusion limits for nTGCs. A linear transformation is utilized to connect the vertex function parameters h_3^V, h_4^V directly to the SMEFT parameters of dimension-8 operators. This transformation is essential for translating the theoretical parameters C_{G+}, C_{G-} , and $C_{\tilde{B}W}$ into the vertex function equivalents:

$$h_4 = -\frac{\text{sign}(c_{G+})}{\Lambda_{G+}^4} \frac{v^2 M_Z^2}{s_W c_W} \quad (6-23a)$$

$$h_3^\gamma = -\frac{\text{sign}(c_{G-})}{\Lambda_{G-}^4} \frac{v^2 M_Z^2}{2c_W^2} \quad (6-23b)$$

$$h_3^Z = \frac{\text{sign}(c_{\tilde{B}W})}{\Lambda_{\tilde{B}W}^4} \frac{v^2 M_Z^2}{2s_W c_W} \quad (6-23c)$$

For simplify, we denote $h_4 = h_4^Z, h_4^Z = \frac{c_W}{s_W} h_4^\gamma$.

The ultimate goal is to establish constraints on the EFT nTGC parameters $C_{G+}/\Lambda_{G+}^4, C_{G-}/\Lambda_{G-}^4, C_{\tilde{B}W}/\Lambda_{\tilde{B}W}^4$, and then convert these constraints into limits for h_3^V, h_4^V parameters. By analyzing the behaviour of high energy photons produced in association with Z bosons, this approach probes the effectiveness and scope of the SMEFT in capturing and describing potential new physics scenarios. Through this method, the vertex function not only enhances the understanding of the interaction dynamics but also provides a basis for testing the predictions of new physics within the SMEFT framework.

6.6.4 Limit Setting

In the SMEFT framework, constraints on the coefficients of dimension-8 operators are extracted through robust statistical limits. These constraints are essential for exploring how new physics may influence the observed phenomena.

Establishing Constraints through Profile Likelihood Methods To assess the potential impact of nTGCs, the analysis uses a one-dimensional profile likelihood function. This ap-

proach involves setting all other nTGC parameters to zero and to focus solely on the influence of one parameter at a time, simplifying the analysis and enhancing the precision. For analysis involving interactions between pairs of nTGC parameters, two-dimensional constraints are varied, allowing exploration of parameters interdependencies and their collective effects, displayed in a 2D plane.

Application of Exclusion Limits Exclusion limits are derived from the analysis of the unfolded leading photon transverse momentum distribution, chosen for its sensitivity to potential new physics effects of nTGC especially, in high p_T region. These limits incorporate systematic uncertainties for each nTGC parameters, ensuring robust and comprehensive constraints.

Conversion to Vertex Function Parameters The exclusion limits obtained from the SMEFT parameters are then converted into constraints on the h_3^V, h_4^V form factors where $V = Z, \gamma$, using the vertex function approach as outlined in Eq. 6–23c. This conversion relates theoretical SMEFT parameters to phenomenologically measurable quantities, providing a practical basis for comparing theoretical predictions with experimental results.

6.6.4.1 One-dimensional Constraints

This section focuses on establishing one-dimensional limits for individual nTGC parameters and deriving constraints for form factors. The process involves obtaining exclusive constraints for dimension-8 operators from the SMEFT, subsequently transforming these into constraints for specific form factors.

For the dimension-8 operators O_i , expected constraints provide the 95% confident limits incorporating all relevant systematic uncertainties, as detailed in Table 6–10 and displayed in Fig. 6–12.

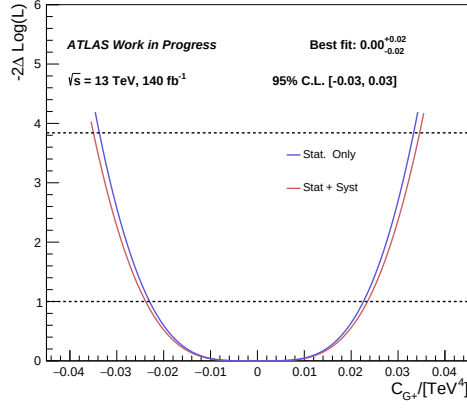
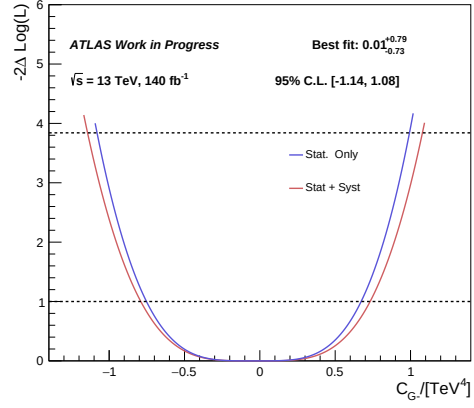
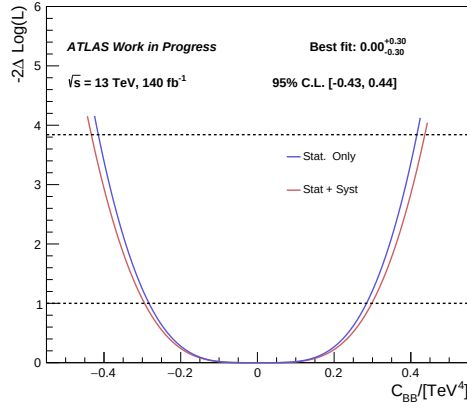
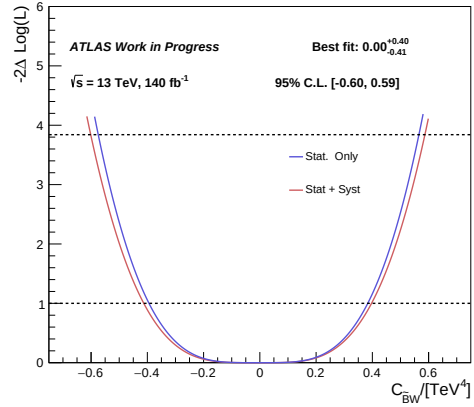
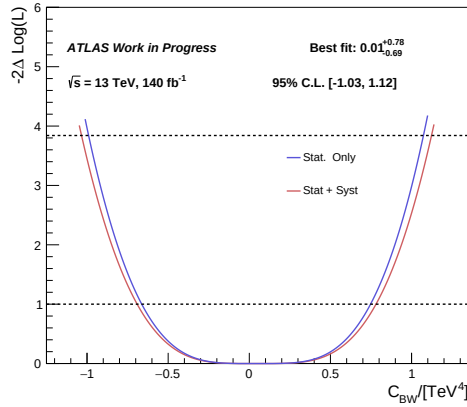
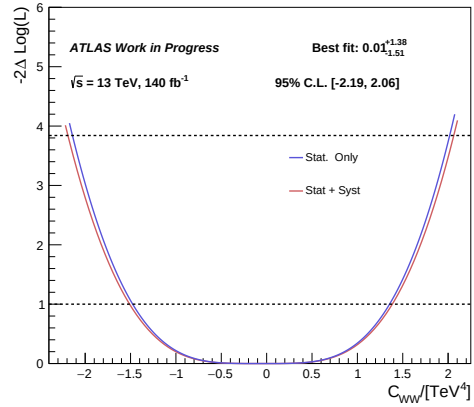
(a) O_{G+} (b) O_{G-} (c) O_{BB} (d) $O_{\bar{B}W}$ (e) O_{BW} (f) O_{WW}

Figure 6–12 A scan of the dimension-8 operators O_j couplings within the SMEFT approach and obtained from the unfolded p_T^γ distribution from pseudo data. All systematic uncertainties, including 0.83% uncertainty related to luminosity, are integrated into the EFT fitting procedure for a comprehensive evaluation.

Parameters	Expected Limits [TeV^{-4}] at 95% C.L.
C_{G+}	[-0.03, 0.03]
C_{G-}	[-1.14, 1.08]
C_{BB}	[-0.43, 0.43]
$C_{\bar{B}W}$	[-0.60, 0.59]
C_{BW}	[-1.03, 1.12]
C_{WW}	[-2.19, 2.06]

Table 6–10 Expected exclusive limits on Wilson coefficients of six dimension-8 operators within the SMEFT at a 95% C.L., with all systematic uncertainties included.

At the same time, the expected constraints on form factors h_i^V are outlined in Table 6–11 derived using the vertex function approach, where these form factors consider the most general $Z\gamma V^*$ vertex and V can be Z, γ . This method corrects previous overestimations by implementing a fully gauge-invariant treatment and adhering to the $SU(2) \times U(1)$ symmetry. The refinement provided by the latest nTGC formulation incorporates additional dimension-8 operators, ensuring more accurate and theoretical deviation of nTGC parameters. This updated approach establishes a non-trivial relationship among the form factors and enhances the theoretical consistency of the nTGC analysis.

Form Factors	Expected Limits at 95% C.L.
h_4^γ	$[-2.3 \times 10^{-5}, 2.3 \times 10^{-5}]$
h_4^Z	$[-4.1 \times 10^{-5}, 4.2 \times 10^{-5}]$
h_3^γ	$[-3.5 \times 10^{-4}, 3.7 \times 10^{-4}]$
h_3^Z	$[-3.6 \times 10^{-4}, 3.5 \times 10^{-4}]$

Table 6–11 Expected limits for form factors from the Effective Vertex approach at a 95% C.L., with all systematic uncertainties included.

6.6.4.2 Two-dimensional Constraints

This study also extended to two-dimensional limits for pairs of nTGC parameters, enhancing the understanding of the sensitivity relationship between these parameters. Using the same transformation equations listed in Eq. 6–23c, this analysis presents the correlation relationships between pairs of nTGC form factors as contour plots in 2D plane.

Fig. 6–13 demonstrates the correlation between h_3^V and h_4^V form factors, providing a comprehensive view of the interactions within this space. The contour plots are defined by con-

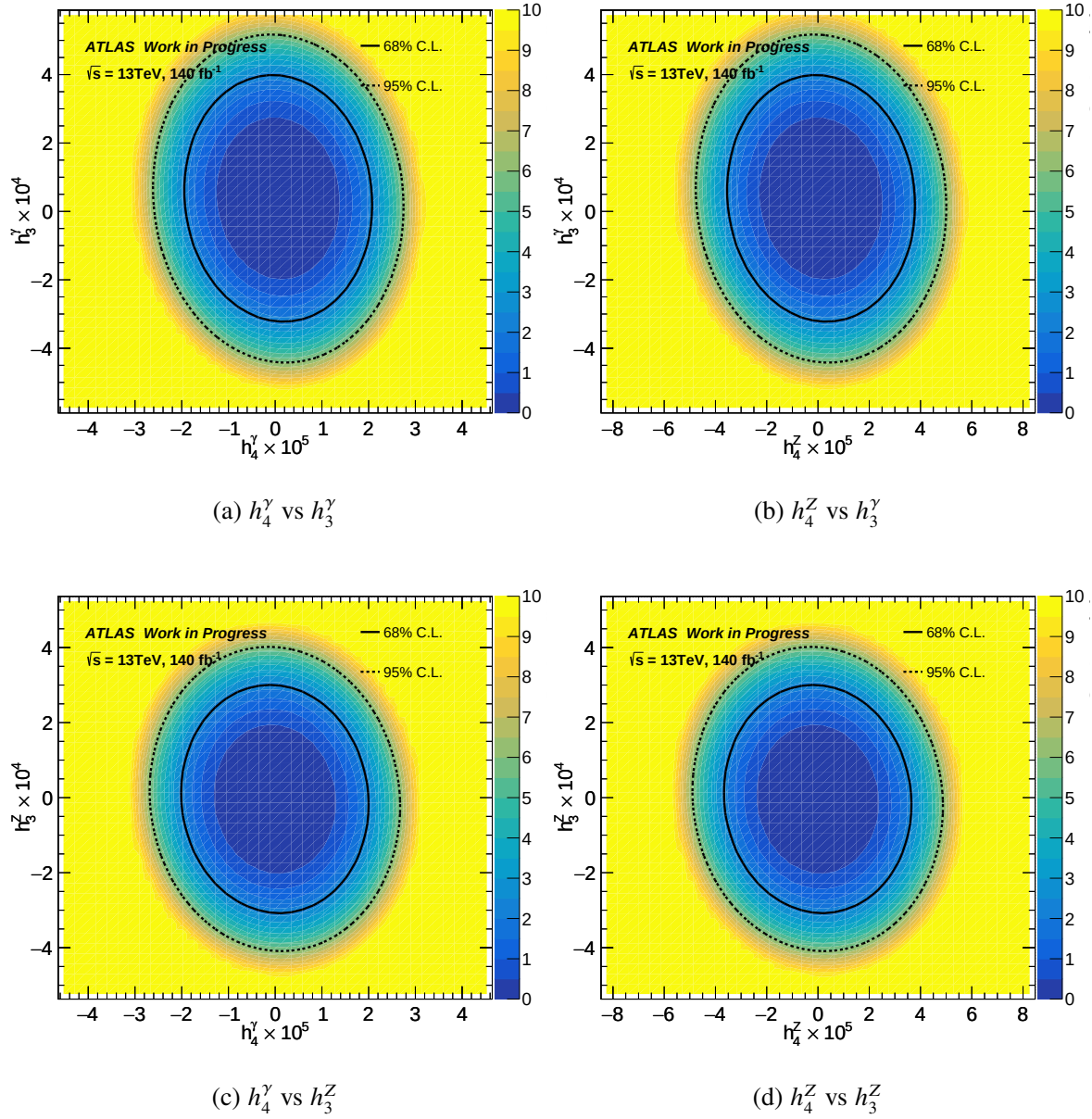


Figure 6–13 The expected limits of contour plots for pairs of nTGC coupling parameters at 95% C.L. plotted in 2D plane. The ellipses on the plots represent the correlations between each pair of form factors, and z-axis denotes $-2\Delta\log(L)$.

fidence levels: the dashed line ellipse indicates the 95% confidence level, and the solid line ellipse represents the 68% confidence level. These visual representations are interpreting the complex relationships and enhancing the overall understanding of the theoretical underpinnings and experimental validations within the SMEFT framework.

We also need to mention that a notable correlation displays in the contour plot of the correlation between h_3^Z and h_3^γ , as shown in Fig. 6–14, and the difference observed from theoretical predictions, attributed to the unique terms considered during the fitting process. The discrepancy arises from the distinctive terms incorporated during the fitting process.

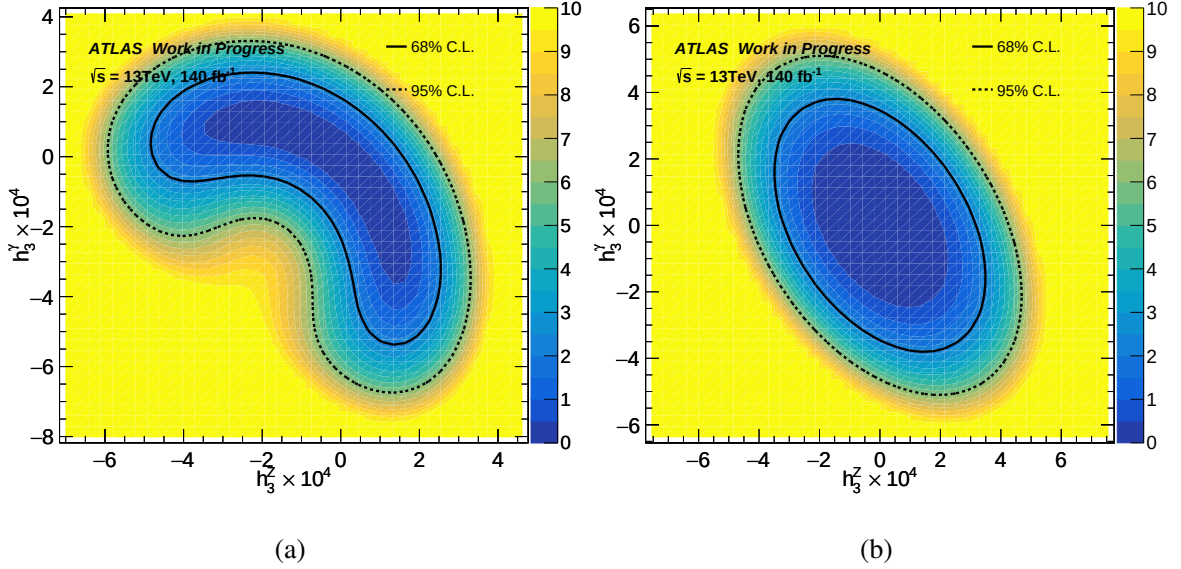


Figure 6–14 Contour plot for h_3^γ and h_3^Z displayed at 95%, derived from different assumptions.

The ellipses highlight the correlations between these parameters.

(a) The left plot shows contours accounting for both pure quadratic BSM terms and the interference with SM term, illustrating a more complex consideration and the impact on the correlation. (b) The right plot focuses exclusively on contour derived from pure quadratic BSM terms.

Unlike the simplified theoretical calculation that only accounts for the pure quadratic nTGC terms, our analysis includes both pure quadratic terms and interference terms that represent interference between the SM and quadratic contributions, as depicted in Fig. 6–14 (a). This comprehensive approach enhances our analysis but also introduces variations from the SM predictions due to the added complexity of the interference terms. These variations underscore the significant impact of model selection on the extraction of nTGCs from the data.

6.6.5 Unitarization Study

The SMEFT framework, while invaluable, has inherent limitations regarding the validity at arbitrarily high energy levels, which can lead to violation of the unitarity. In SMEFT, operators with mass dimensions $d \geq 4$ can yield interaction probabilities that increase without bound, potentially resulting in unitarity^[212] violations where the probability of an interaction exceeds one. To address this issue, the SMEFT approach requires careful consideration of the energy scales at which these theories remain valid.

Unitarity and Cutoff Scales Physical limits on these interactions are typically established by incorporating cutoff scales Λ , beyond which the SM terms maintain consistency without leading to nonphysical results. This study specifically investigates the implications of various cutoff scales on the validity of dimension-8 operators by scanning the limits against several potential values of Λ . This approach ensures that the extensions to the SM encapsulated by these operators do not violate unitarity at high energies.

Furthermore, corresponding form factors h_3^V and h_4^V are presented in Fig. 6–15 - 6–17.

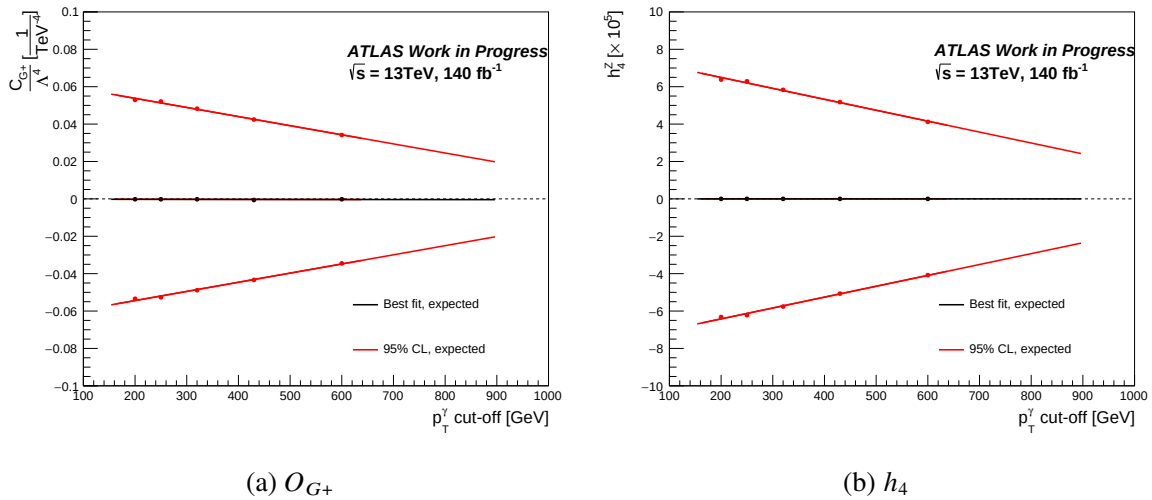


Figure 6–15 Depicts the evolution of confidence intervals for EFT anomalous coupling parameters across different p_T^γ cutoff scales. The confidence intervals for each data point is calculated under the constraints that anomalous couplings do not violate unitarity.

The form factors (h_i^V , where $i=3,4$ and $V=Z, \gamma$) allow dimension-8 operators to remain valid up to the examined high energy limits, mitigating issues such as infinite cross sections and the breakdown of quantum field theory unitarity. The constraints obtained for these

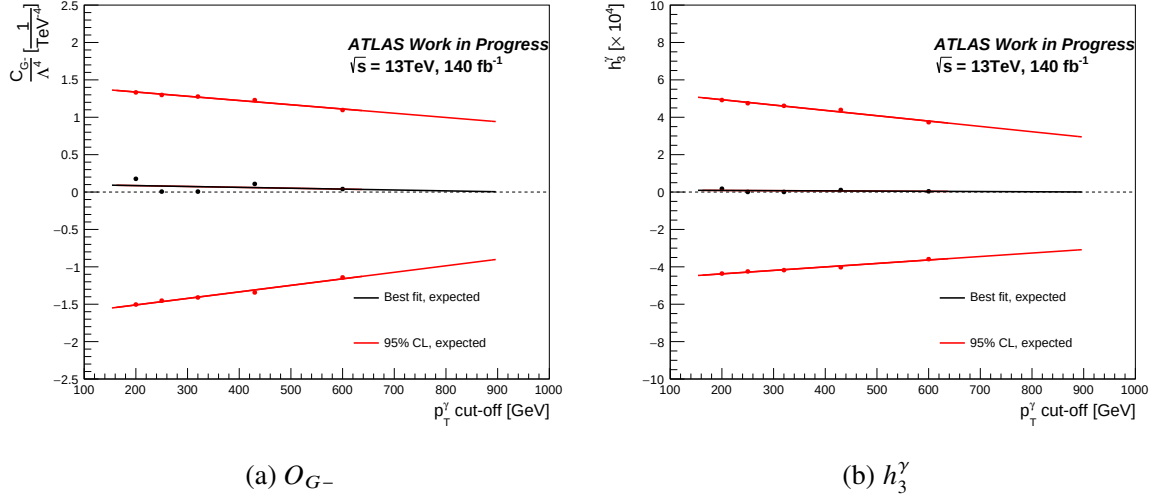


Figure 6-16 Depicts the evolution of confidence intervals for EFT anomalous coupling parameters across different p_T^γ cutoff scales. The confidence intervals for each data point is calculated under the constraints that anomalous couplings do not violate unitarity.

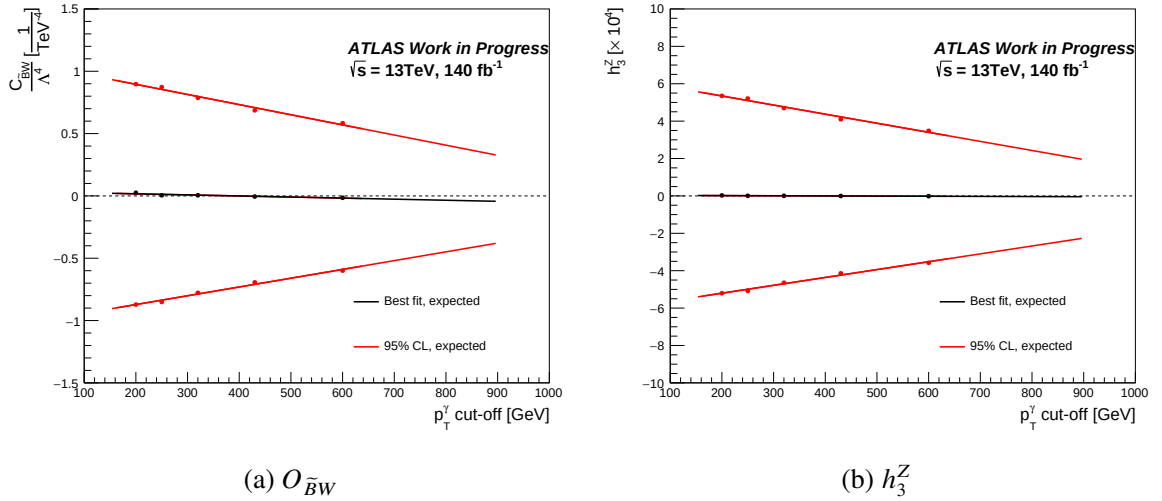


Figure 6-17 Depicts the evolution of confidence intervals for EFT anomalous coupling parameters across different p_T^γ cutoff scales. The confidence intervals for each data point is calculated under the constraints that anomalous couplings do not exceed SM predictions at specific p_T^γ values.

dimension-8 operators and form factors are consistent with theoretical expectations from the latest nTGC formulation, validating the SMEFT framework extension to these energy scales.

Consistency with Theoretical Predictions The constraints derived from the vertex function approach are shown to align with current theoretical predictions in the latest nTGC for-

mulation. This alignment underscores the effectiveness of the SMEFT framework in providing a consistent and theoretical description of nTGCs, even as it extends to higher energy scales.

This detailed examination of unitarity concerns in the SMEFT framework not only enhances the robustness of theoretical predictions but also ensures that the extensions proposed are physically reasonable and mathematically consistent across a range of energy scales.

6.7 Conclusion

This analysis provides a detailed summary of the fiducial cross section measurements for $Z\gamma$ production featuring fully leptonic decays into electron and muon pairs of opposite signs. These measurements were carried out using data collected by the ATLAS detector from 2015 to 2018, amounting to an integrated luminosity of approximately 140 fb^{-1} at a center-of-mass energy of 13 TeV.

This analysis also discusses the differential distribution of p_T^γ , which are crucial for applying the SMEFT approach in both one-dimensional and two-dimensional limits. As well it incorporates a novel fully gauge invariant treatment to study additional dimension-8 operators O_{G+} and O_{G-} , alongside the conventional dimension-8 operators. The study updates the constraints on the SMEFT parameters and vertex function parameters, presenting the most recent experimental constraints on dimension-8 operators based on new formulations.

Chapter 7 Search for nTGCs in $Z\gamma(\ell^+\ell^-\gamma)$ Production at Future Lepton Collider

Neutral Triple Gauge Couplings (nTGCs) are absent at the dimension-6^[32,213] level in the Standard Model (SM) and only appear at the dimension-8^[33-34] level within the Standard Model Effective Field Theory (SMEFT). These operators offer a unique opportunity for probing physics beyond the SM. This chapter examines the nTGCs through the reaction $e^+e^- \rightarrow Z\gamma$ with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) at the Circular Electron Positron Collider (CEPC)^[36]. This investigation utilizes a center-of-mass energy of $\sqrt{s} = 240$ GeV with an integrated luminosity of 20 ab^{-1} . Sensitivities to new physics scales associated with dimension-8 nTGC operators is explored by measuring the corresponding form factors through detailed detector-level simulation.

7.1 Introduction

7.1.1 Opportunities and Challenges in nTGC Detection at Lepton Colliders

Neutral Triple Gauge Couplings (nTGCs)^[10-14] present an intriguing probe into physics beyond the Standard Model (SM)^[1,19], emerging only at the dimension-8 level within the Standard Model Effective Field Theory (SMEFT)^[6-7]. The nTGCs provide unique insights into high-energy interactions, offering potential discoveries of new dynamics and particles. The study of nTGCs can help to understand aspects of electroweak symmetry breaking and possible extensions of the SM, thereby testing the robustness of the current theoretical framework. By probing nTGCs, exploring phenomena at energy scale beyond the electroweak regime potentially can uncover interactions mediated by new massive particles or novel strong forces.

Lepton colliders, such as the Circular Electron Positron Collider (CEPC)^[36], are particularly advantageous for nTGC searches due to their clean experimental environments and precise measurement capabilities. Processes like $e^+e^- \rightarrow Z\gamma$, where the Z boson decays into lepton pairs ($\ell^+\ell^-$) serves as effective channels for nTGC production. The high resolution in angular measurements and precise determination on beam momentum and direction

can significantly enhance the detection sensitivity for nTGCs.

The sensitivity to nTGCs lies on the potential to reveal new physics, the distinct production mechanisms, and the optimal conditions provided by lepton colliders. This research endeavors to expand our understanding of fundamental interactions and rigorously test theoretical models predicting new phenomena.

7.1.2 Theoretical Framework of nTGCs

The SMEFT is a powerful framework for studying possible new physics beyond the SM in a model-independent way. The SMEFT incorporates known elementary particles with SM quantum numbers and interactions with mass-dimension $d \leq 4$, while also including higher-dimensional interactions ($d > 4$) that could arise from new physics at energy scales beyond the electroweak scale. Such interactions may involve exchanges of new massive particles or novel strong dynamics.

A comprehensive analysis of dimension-6 operators should account for their quadratic effects on event rates, which scale quartically with the new physics scale. This necessitates considering linear interference between dimension-8 SMEFT operators and SM amplitudes, which also scale quartically^[214-216]. Notably, processes lacking dimension-6 operator contributions are dominated by dimension-8 operators, making nTGCs particularly significant. These processes include quartic neutral vector-boson interactions and neutral triple gauge couplings.

nTGCs are absent in the SM and dimension-6 SMEFT operators but appear at the dimension-8 level, offering a unique opportunity to probe new physics. Direct experimental investigations of nTGCs involve measuring the corresponding form factors. Recent theoretical work has proposed a consistent formulation of nTGC form factors, matching them with gauge-invariant dimension-8 effective operators of the SMEFT. This formulation imposes nontrivial relations among the nTGC form factors, providing accurate predictions for their contributions to high-energy scattering amplitudes^[13-14].

The dimension-8 SMEFT effective Lagrangian is formulated as follows:

$$\mathcal{L}_{\text{SMEFT}} = \sum_j \frac{c_j}{\Lambda^4} \mathcal{O}_j = \sum_j \frac{\text{sign}(c_j)}{\Lambda_j^4} \mathcal{O}_j \quad (7-1)$$

where c_j are dimensionless coefficients that may be $\mathcal{O}(1)$ and can have either sign. The effective cutoff Λ for the new physics scale is related to Λ_j via $\Lambda_j \equiv \Lambda/|c_j|^{\frac{1}{4}}$.

In this analysis, we consider the following set of CP-conserving dimension-8 nTGC operators (O_{G+} , O_{G-} , $O_{B\widetilde{W}}$, $O_{\widetilde{B}W}$):

$$gO_{G+} = \widetilde{B}_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} + D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (7-2a)$$

$$gO_{G-} = \widetilde{B}_{\mu\nu} W^{\alpha\mu\rho} (D_\rho D_\lambda W^{\alpha\nu\lambda} - D^\nu D^\lambda W_{\lambda\rho}^\alpha) \quad (7-2b)$$

$$O_{\widetilde{B}W} = iH^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + h.c. \quad (7-2c)$$

$$O_{B\widetilde{W}} = iH^\dagger (D_\sigma \widetilde{W}_{\mu\nu}^\alpha + D_\sigma \widetilde{B}_{\mu\nu} B^{\mu\sigma}) D^\nu H + h.c. \quad (7-2d)$$

The nTGC vertex $Z\gamma V^*$ ($V = Z, \gamma$) can be expressed in terms of nTGC form factors (h_3^V, h_4^V) as follows:

$$\Gamma_{Z\gamma V^*}^{\alpha\beta\mu(8)}(q_1, q_2, q_3) = \frac{e(q_3^2 - M_V^2)}{M_Z^2} \left[(h_3^V + \frac{h_4^V}{2M_Z^2}) q_{2\nu} \epsilon^{\alpha\beta\nu} + \frac{h_4^V}{M_Z^2} q_2^\alpha q_{3\nu} q_{2\sigma} \epsilon^{\beta\mu\nu\alpha} \right] \quad (7-3)$$

By aligning the nTGC form factor framework with the gauge-invariant dimension-8 nTGC operators, we derived a significant relationship between form factors: $h_4^\gamma = \frac{c_W}{s_W} h_4^Z$. For convenience, we denote h_4^Z as h_4 . Consequently, we identify three independent form-factor parameters (h_4, h_3^Z, h_3^γ), which can be determined by matching the gauge-invariant dimension-8 operators (O_{G+} , O_{G-} , $O_{B\widetilde{W}}$, $O_{\widetilde{B}W}$) within the broken phase of the electroweak gauge group $SU(2)_L \times U(1)_Y$. These form factors (h_4, h_3^Z, h_3^γ) are intrinsically related to the cutoff scales (Λ_{G+} , Λ_{G-} , $\Lambda_{B\widetilde{W}}$, $\Lambda_{\widetilde{B}W}$) associated with the respective dimension-8 nTGC operators.

$$h_4 = -\frac{1}{[\Lambda_{G+}^4]} \frac{v^2 M_Z^2}{s_W c_W} \quad (7-4a)$$

$$h_3^\gamma = -\frac{1}{[\Lambda_{G-}^4]} \frac{v^2 M_Z^2}{2c_W^2} = -\frac{1}{[\Lambda_{B\widetilde{W}}^4]} \frac{v^2 M_Z^2}{s_W c_W} \quad (7-4b)$$

$$h_3^Z = \frac{1}{[\Lambda_{\widetilde{B}W}^4]} \frac{v^2 M_Z^2}{2s_W c_W} \quad (7-4c)$$

We define the term $[\Lambda_j^4] = \text{sign}(c_j) \Lambda_j^4$ and $[\Lambda_j^{-4}] = \text{sign}(c_j) \Lambda_j^{-4}$.

Subsequently, we conduct a comprehensive detector-level simulation and sensitivity analysis of the dimension-8 nTGC effective operators, focusing on measuring the nTGC form factors in the $e^+e^- \rightarrow Z\gamma$ process at the future lepton collider.

7.2 Event Generation and Simulation at CEPC

7.2.1 Overview of CEPC

The Circular Electron Positron Collider (CEPC)^[36,217] is a proposed dedicated particle collider designed to function both as a Higgs boson factory and a Z boson factory. It operates with a center-of-mass energy $\sqrt{s} = 240$ GeV for Higgs boson production and $\sqrt{s} = 91.2$ GeV for Z boson production. Additionally, it can conduct threshold scans for W boson production at $\sqrt{s} = 160$ GeV. The CEPC aims to generate substantial yields, and expected to produce approximately 1 million Higgs bosons, and 10^{12} Z bosons in a two-year period. Additionally, about 10^8 W bosons are produced during one-year operation. Table 7–1 summarizes the projected operational modes and the anticipated yields of H, W, and Z bosons under different scenarios.

Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ GeV	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	115	16	5	0.5
Integrated luminosity (ab^{-1})	60	4.2	13	0.65
Z boson yields	2.5×10^{12}	-	-	-
W boson yields	-	1.3×10^8	-	-
Higgs boson yields	-	-	2.6×10^6	-
$t\bar{t}$ yields	-	-	-	0.4×10^6

Table 7–1 Projected operational modes of CEPC and associated yields of Higgs, W, and Z bosons, as well as $t\bar{t}$ production^[217]. Estimation based on two interaction points and the integrated luminosities, respectively.

The CEPC, with a 100 km circumference, balances performance and cost-efficiency while supporting future upgrades, such as incorporating a Super Proton-Proton Collider (SPPC) with a 125 TeV center-of-mass energy. The design leverages advanced technologies, including superconducting RF cavities and cryogenic systems. Following initial operations, the CEPC will undergo an upgrade to facilitate $t\bar{t}$ production, increasing the center-of-mass energy to 360 GeV and extending the operational capabilities. This upgrade will enhance its relevance and scientific output, including generating 0.4 million $t\bar{t}$ events.

The CEPC is set to become a cornerstone of particle physics research, producing vast quantities of Higgs, W, and Z bosons with high precision. Its flexible design will advance

our understanding of fundamental interactions and potentially uncover new physics beyond the SM. The SPPC, sharing the same tunnel, will be positioned adjacent to the outer wall, facilitating simultaneous operation with the CEPC.

7.2.2 Conceptual Detector Design

The CEPC experiment aims to conduct an extensive study of Higgs boson properties, necessitating detectors with exceptional performance in identifying and reconstructing charged leptons, photons, jets, and missing transverse energy. Effective flavor tagging of jets, particularly those originating from b , c , or light quarks, is crucial for isolating hadronic decay channels of the Higgs boson. The baseline detector concept of the CEPC integrates several critical components to meet the high requirements of precision particle physics research. The tracking system comprises a Silicon Vertex Detector with six pixel layers for accurate tracking and vertex reconstruction, the Silicon Tracker with three barrel layers and six forward disks on each side for precise momentum measurement, and a Time Projection Chamber (TPC) with 220 radial readout for high granularity tracking and particle identification. The calorimetry system is composed of the Electromagnetic Calorimeter (ECAL) and the Hadronic Calorimeter (HCAL). The ECAL, constructed from W/Si with $24 X_0$ and $5\times 5 \text{ mm}^2$ cells in 30 layers, measures the energy of electrons and photons. The HCAL, made of Fe/RPC with 6λ and $10\times 10 \text{ mm}^2$ cells in 40 layers, assesses the energy of hadrons.

Tracking system	
Vertex detector	6 pixel layers
Silicon tracker	3 barrel layers, 6 forward disks on each side
Time projection chamber	220 radial readouts
Calorimetry	
ECAL	W/Si, $24X_0$, $5\times 5 \text{ mm}^2$ cell with 30 layers
HCAL	Fe/RPC, 6λ , $10\times 10 \text{ mm}^2$ cell with 40 layers
Performance	
Tracking momentum resolution	$\Delta(1/p_T)2 \times 10^{-5}(1/\text{GeV})$
Impact parameter resolution	$5\mu\text{m} \oplus 10\mu\text{m}/[(p/\text{GeV})(\sin\theta)^{3/2}]$
ECAL energy resolution	$\Delta E/E 10\%/\sqrt{E/\text{GeV}} \oplus 1\%$
HCAL energy resolution	$\Delta E/E 60\%/\sqrt{E/\text{GeV}} \oplus 1\%$

Table 7–2 Baseline specifications and performance parameters of the CEPC detector.

Drawing inspiration from the international Large Detector (ILD)^[218], the preliminary detector model for the CEPC adheres to the particle flow algorithm^[219-221]. This strategy optimally combines individual sub-detectors to reconstruct visible final-state particles, proving particularly advantageous for tagging complex objects such as τ leptons and jets.

The detector concept emphasizes broad solid angle coverage, excellent particle identification, and precise energy and momentum measurements. Efficient vertex reconstruction is essential for locating particle interaction origins, while jet reconstruction and flavor tagging are key for analyzing hadronic jets. The detector must also adapt to varying beam conditions, such as different bunch spacings and synchrotron radiation powers, depending on the operational mode (Higgs, Z or W). This flexibility ensures that the CEPC can achieve diverse physics goals, from detailed Higgs boson studies to exploring new physics beyond the SM. The geometric configurations and performance metrics of the CEPC detector, summarized in Table. 7-2, ensures the readiness for high-precision physics analyses.

7.2.3 Event Generation, Simulation, and Reconstruction at CEPC

The generation and simulation of physics events are crucial for CEPC with several key components involved as illustrated in Fig. 7-1

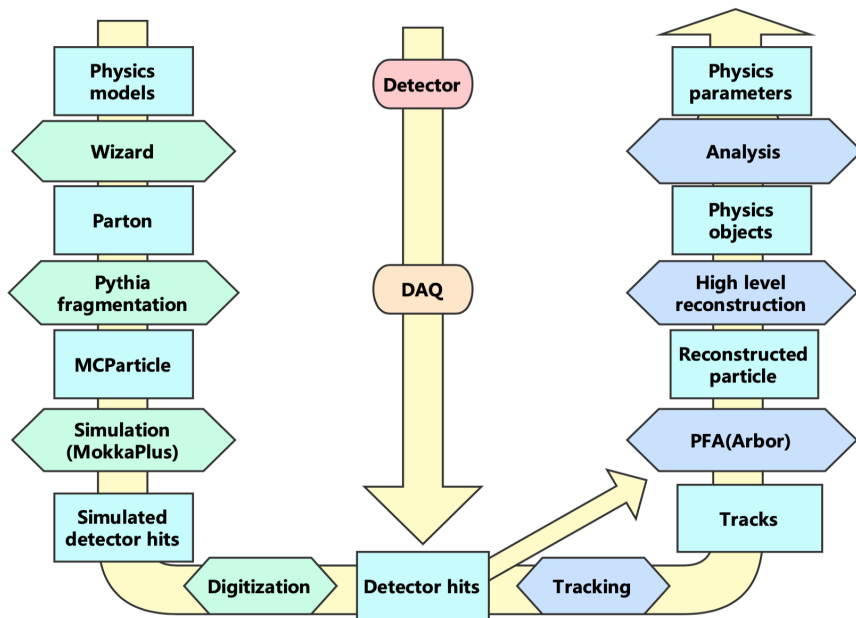


Figure 7-1 Flowchart of CEPC simulation study.

The primary event generator for CEPC physics performance studies is the `Whizard` package^[222]. It includes specialized CEPC beam parameters for accurate simulation of Standard Model (SM) processes, including Higgs boson signals and associated backgrounds. For beyond the SM (BSM) physics, `MADGRAPH`^[223] and `PYTHIA8`^[86,224] generators are used.

CEPC employs the `MOKKAPLUS`^[225] framework, based on `GEANT4`^[226-227] for detector simulation. `MOKKAPLUS`, enhanced from `MOKKA`, constructs the detector geometry and simulate energy deposits using `GEANT4` libraries. This process includes digitizing the simulated energy deposits to replicate actual detector hits accurately. Continuous refinement ensures the digitization framework matches real experimental data.

Process	Cross section	Events in 20 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \rightarrow \ell^+\ell^-H$	20.56	4.1×10^5
$e^+e^- \rightarrow \nu\bar{\nu}H$	46.29	9.3×10^5
$e^+e^- \rightarrow q\bar{q}H$	136.81	2.7×10^6
Other processes, cross section in pb		
$e^+e^- \rightarrow \ell^+\ell^-$	34.86	7.0×10^8
$e^+e^- \rightarrow \nu\bar{\nu}$	50.50	1.0×10^9
$e^+e^- \rightarrow q\bar{q}$	54.11	1.1×10^9
$e^+e^- \rightarrow WW$	9.08	1.8×10^8
$e^+e^- \rightarrow ZZ$	1.41	2.3×10^7

Table 7–3 Cross sections and yields for various processes at CEPC.

Table. 7–3 outlines the anticipated event yields for various processes at an integrated luminosity of 20 ab^{-1} . Cross section calculations for most processes are performed using the `Whizard` package.

Reconstruction starts with track reconstruction using the `Clupatra` model, known for its high performance. The Particle Flow Algorithm (PFA)^[228-230] is key for CEPC reconstruction process, converting all detector hits into final state particles. A comprehensive particle flow reconstruction toolkit, `ARBOR`^[220], has been developed to reconstruct charged particles, photons, and neutral hadrons with high precision, significantly improving the measurement accuracy of complex physics objects such as τ and jets. The PFA provides a consistent global description of the event, enhancing the efficiency and purity, it also supports fast simulation

algorithm for replicating final state particle information from the generator level to the detector level. By integrating these advanced simulation and reconstruction techniques, CEPC ensures high precision and efficiency in analyzing high-energy physics events for supporting the research objectives.

7.2.4 nTGC Signal Production

The probe of dimension-8 nTGC is performed via the reaction of $e^+e^- \rightarrow Z\gamma$ followed by $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) decays, as illustrated in Fig. 7-2. Detector level simulations and analyses are conducted at the CEPC with a center-of-mass energy $\sqrt{s} = 240$ GeV and an integrated luminosity of 20 ab^{-1} using a model-independent approach.

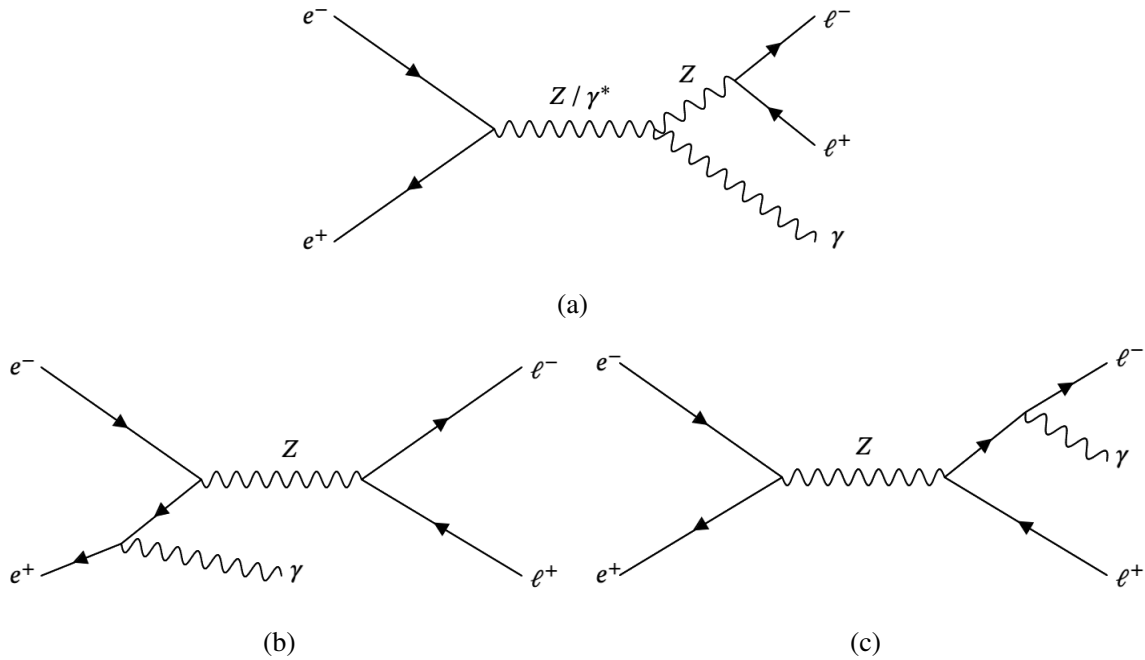


Figure 7-2 Feynman diagrams for the reaction $e^+e^- \rightarrow Z\gamma$. Diagram (a) represents the signal process involving the nTGC vertex $Z^*Z\gamma$ or $\gamma^*Z\gamma$, while the diagrams (b) and (c) depict the SM $Z\gamma$ contributions, including the Initial-State-Radiation (ISR) photon and Final-State-Radiation (FSR) photon processes.

The signal events for this analysis are generated using MADGRAPH_AMC@NLO and PYTHIA8. The nTGC formulation described in Section 7.1.2 is implemented and imported to the event generators through FeynRules for generating nTGC events at the matrix element level at leading order. Subsequently, PYTHIA8 is utilized for parton showering, fragmen-

tation, and simulating the underlying events. For accuracy, nTGC samples consist of three components: the Standard Model (SM) term, the interference term between the SM and nTGC, and the squared nTGC term. These components are decomposed from the $Z\gamma$ cross section and generated independently, ensuring precise sample production.

Form Factors	SM	h_4	h_3^γ	h_3^Z	(h_4, h_3^γ)	(h_4, h_3^Z)	(h_3^γ, h_3^Z)
h_i^V	-	0.28	0.16	0.36	(0.83, 0.49)	(0.83, 1.07)	(0.49, 1.07)
$\sigma_{Z\gamma}$ [fb]	2552	2616	2752	2712	3732	3613	5120

Table 7–4 Benchmark values for the form factors h_4 , h_3^γ , and h_3^Z (second row) and the corresponding cross sections for $Z\gamma$ production (third row).

The contribution of three nTGC form factors (h_4 , h_3^γ , and h_3^Z) are illustrated using benchmark values provided in Table 7–4. The dependence of the $Z\gamma$ cross section on nTGC form factors (h_j) and the cutoff scale (Λ_j) is expressed as:

$$\sigma_{Z\gamma} = \sigma_0 + \bar{\sigma}_1 h_j + \bar{\sigma}_2 h_j^2 = \sigma_0 + \tilde{\sigma}_1 [\Lambda_j^{-4}] + \tilde{\sigma}_2 [\Lambda_j^{-8}] \quad (7-5)$$

Here, σ_0 is the SM contribution, $\bar{\sigma}_1$ or $\tilde{\sigma}_1$ results from interference between SM and nTGC contributions, and $\bar{\sigma}_2$ or $\tilde{\sigma}_2$ corresponds to squared nTGC contributions. The notation $[\Lambda_j^{-4}] \equiv \text{sign}(c_j)\Lambda_j^{-4}$ is as defined previously. The benchmark values are selected to yield similar magnitudes for the three cross-section terms (σ_0 , $\bar{\sigma}_1$, $\bar{\sigma}_2$) in Eq. 7–5, so as to optimize the fitting accuracy for the three terms.

Fig. 7–3 demonstrates the results from varying the form factors (h_4 , h_3^γ , h_3^Z), with the fitted curves confirming the dependence of $Z\gamma$ cross section on the nTGC form factors. Utilizing the advanced simulation tools and precise parameterizations, the study provides a robust framework for exploring beyond the SM physics at CEPC.

7.2.4.1 Enhancement of Interference Effects Using Multivariate Techniques

This enhancement employs the ROOT-based Toolkit for Multivariate Data Analysis (TMVA)^[231-232] to improve the analysis of complex extraction for interference term. We specifically utilize Gradient Boosting with Boosted Decision Trees (BDTG)^[233]. This toolkit facilitates the use of various advanced machine learning methods, which significantly enhance the sensitivity.

We focus particularly on the two-dimensional kinematic distributions of the angle ϕ , θ , and θ^* , where ϕ denotes the angle between the scattering plane and the decay plane of Z

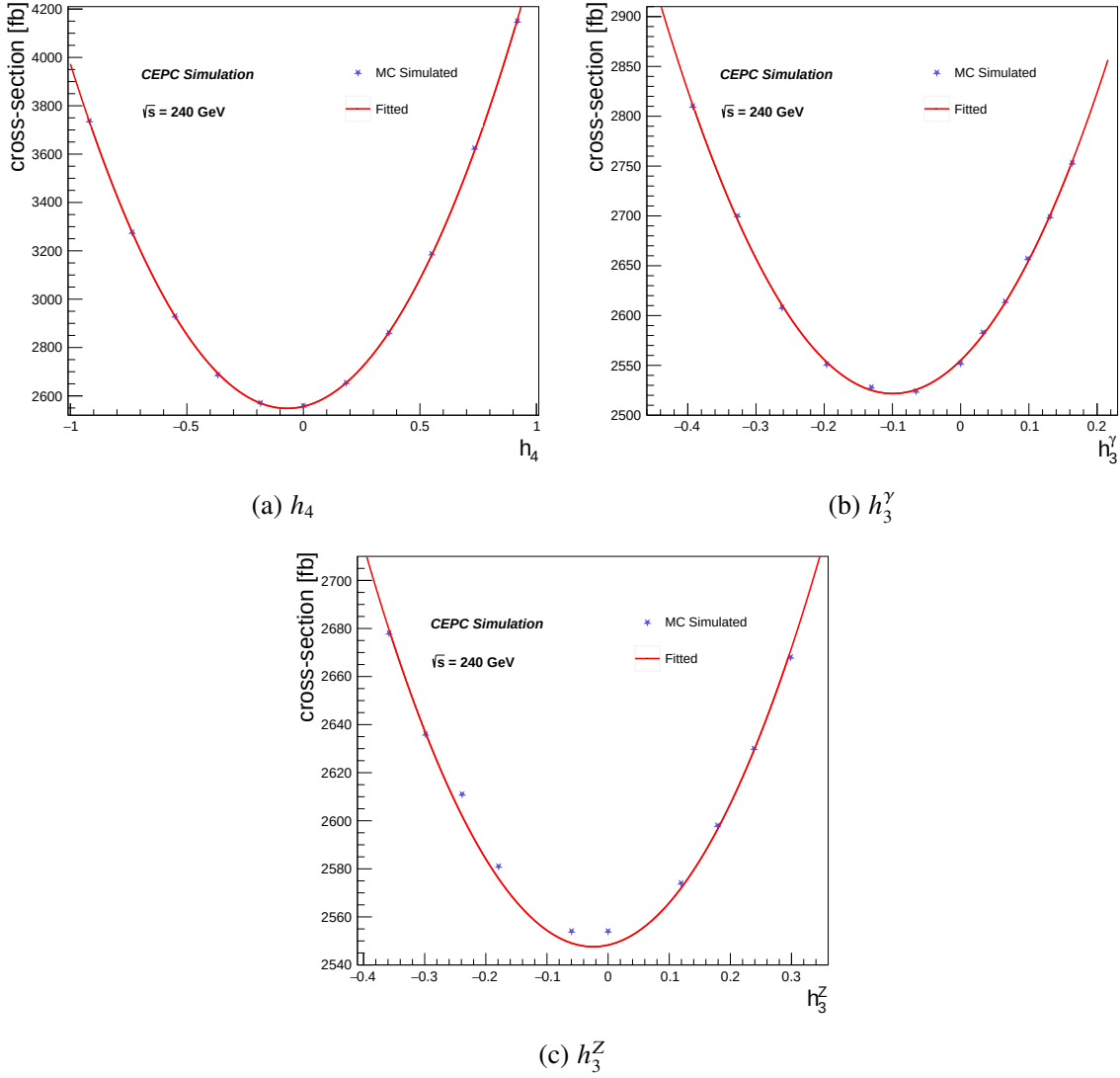


Figure 7-3 Cross sections as functions of the form factors h_4 , h_3^γ , and h_3^Z . The relationship between cross sections and form factors is evaluated by varying the parameter values, which confirm well to the polynomial form of Eq. 7-5. The solid blue stars represent outputs from MADGRAPH_AMC@NLO simulations, while the red solid curves indicate the fits obtained through parameterizations corresponding to Eq. 7-5.

boson, θ is the polar angle of the outgoing Z boson with respect to the initial electron as introduced in Fig. 7-4, and θ^* is the decay angle in the Z rest frame with Z boson direction. These angular measurements are crucial for distinguishing events with different patterns for events with positive and negative cross sections, and are visualized in Fig. 7-5 to demonstrate significant separation.

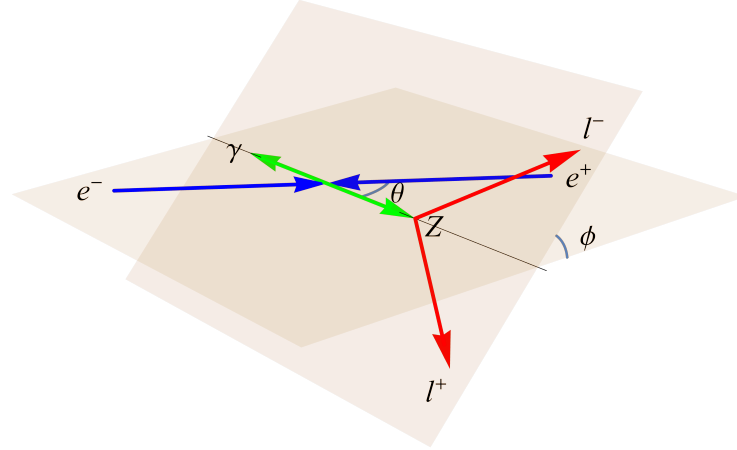


Figure 7-4 Kinematic configuration for the process $pp \rightarrow Z\gamma$, followed by the leptonic decay $Z \rightarrow \ell^+\ell^-$, as observed in the laboratory frame.

Form factors	Truth		With BDTG		Net
	Positive	Negative	Positive	Negative	
h_4	284.01	-197.89	275.93	-189.82	86.12
h_3^γ	279.48	-16.20	264.03	-0.75	263.27
h_3^Z	52.35	-20.45	52.27	-20.37	31.90

Table 7-5 Cross sections in [fb] for interference term of h_4 , h_3^γ , and h_3^Z for events with positive and negative cross sections, comparing MC truth values against results obtained through the BDTG approach.

The variable $u = \cos \theta \times \cos \theta^*$ is defined to enhance the analytical significance. Utilizing the BDTG method, we establish the precise boundaries in the $\phi - u$ plane, allowing to effectively distinguish events with positive and negative cross sections of the interference term. The left panel of the figures display events with positive cross sections, while the right panels show those with negative values, illustrating how the interference terms influence the signal strength and facilitating the extraction of the interference terms. The components derived from this method are applied in the fitting process, using both events with positive and negative cross sections instead of net cross sections as listed in Table 7-5. This approach yields larger effective cross sections, enhancing the sensitivity of our measurements and allowing a more accurate extraction of the nTGC contributions.

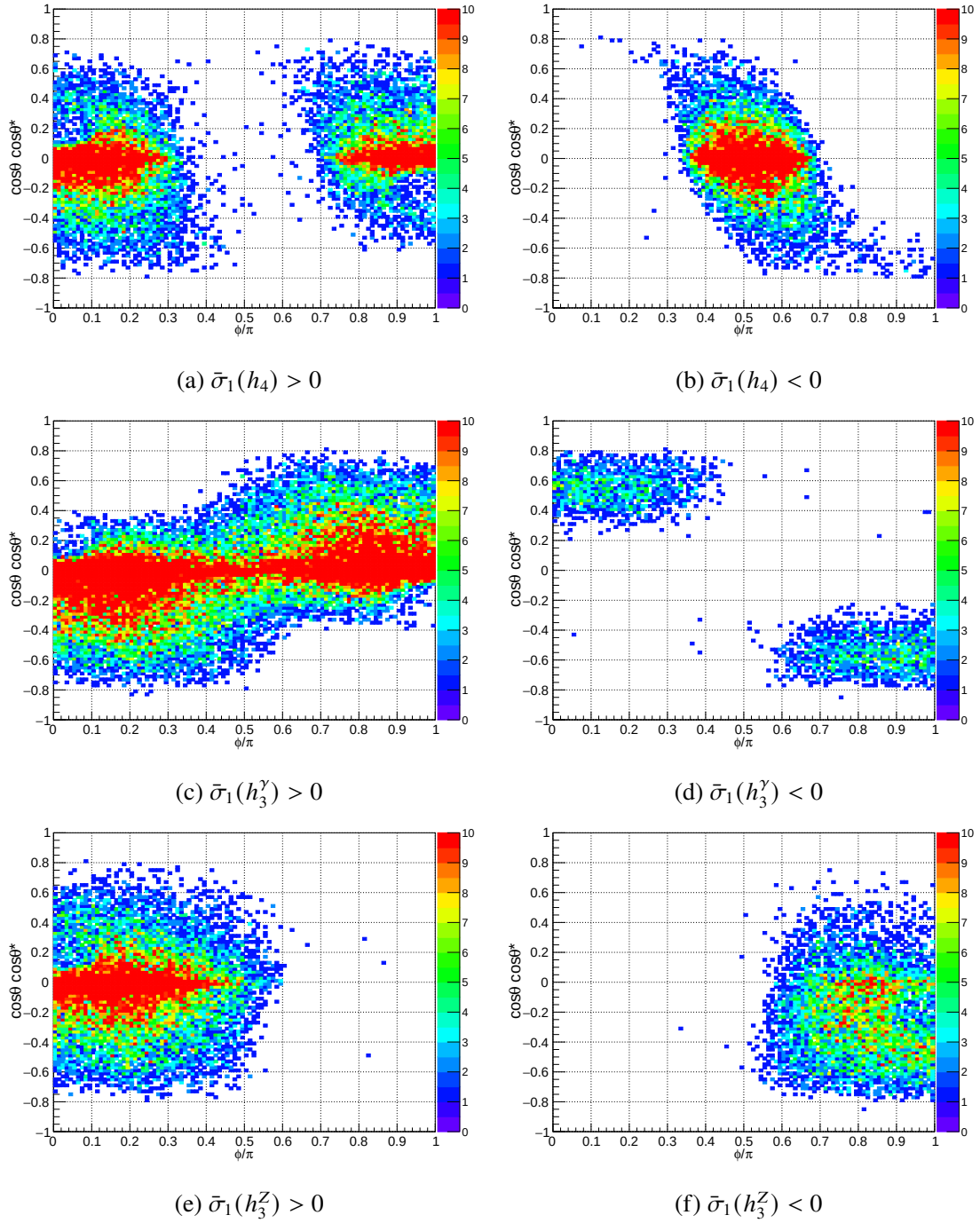


Figure 7-5 Normalized distributions of the angular variables employed to determine the simulated interference events for form factors h_4 , h_3^γ , and h_3^Z . The left panel displays interference events with positive cross sections, while the right panel corresponds to the interference events with negative cross sections.

7.3 Analysis Strategy

The CEPC detector employs the Particle Flow Algorithm (PFA) for event reconstruction, utilizing the Arbor^[220,234] to integrate tracks and calorimeter hits into coherent Particle Flow Objects (PFOs), facilitating advanced particle identification and analysis.

7.3.1 Object Identification and Event Selection

The CEPC detector utilizes the Arbor toolkit to reconstruct and identify leptons and photons with high precision, enhancing the analysis of particle interactions. Leptons, including electrons and muons, are identified through a likelihood-based algorithm LICH^[235] for distinguishing these particles from hadronic components by using detailed inputs from the highly granular calorimeter and tracker. This results in identification efficiencies^[235] for electrons and muons over 99.7% and 99.9%, respectively, ensuring minimal misidentification rates lower than 0.07%. Lepton isolation is ensured by applying the criteria^[236] $E_{\text{cone}}^2 < 4E_\ell + 12.2$, where E_{cone} is the energy within a cone defined by $\cos \theta_{\text{cone}} < 0.98$ around the lepton, and E_ℓ is the energy of the lepton. Furthermore, the spatial separation between two selected leptons must satisfy $\cos \theta_{\mu^+\mu^-} < 0.81$ and $\cos \theta_{e^+e^-} < 0.71$ to ensure proper isolation. Jets, reconstructed from aggregated calorimeter hits and associated tracks, are essential for analyses that require detailed understanding of hadronic components. The optimized clustering algorithms in Arbor ensure that jets are identified effectively. The removal of isolated leptons and photons is required to avoid misreconstruction of jets, supporting and facilitating the interpretation of complex event topologies. All object definitions are summarized in Table 7–6.

The analysis focuses on the evaluation of events characterized by a single photon and a pair of leptons with opposite charges and same flavors (electrons or muons). The event selection criteria, detailed in Table 7–7, are designed to optimize the detection of signals while effectively reducing background contributions.

These selections are carefully refined according to the theoretical framework outlined in Ref.^[12-14], ensuring the exclusion of jets to minimize higher-order SM correction and to isolate enhancements attributable to neutral triple gauge couplings (nTGC) rather than SM processes. This includes stringent constraints such as guaranteeing the mass difference between the di-lepton system and the on-shell Z boson remains under 10 GeV, and that the sum

Objects	Requirements
Electrons	$p_T > 15 \text{ GeV}, \cos \theta < 0.969$
	$E_{\text{cone}}^2 < 4E_\ell + 12.2$
	$ \cos \theta_{e^+e^-} < 0.71$
	(Overlap Removal) $\Delta R(e, j) > 0.4, \Delta R(e, \mu) > 0.4$
Muons	$p_T > 15 \text{ GeV}, \cos \theta < 0.969$
	$E_{\text{cone}}^2 < 4E_\ell + 12.2$
	$ \cos \theta_{\mu^+\mu^-} < 0.81$
Photons	$p_T > 30 \text{ GeV}, \cos \theta < 0.969$
	(Overlap Removal) $\Delta R(\gamma, e) > 0.4, \Delta R(\gamma, \mu) > 0.4$
Jets	$p_T > 25 \text{ GeV}, \cos \theta < 0.969$
	(Overlap removal) $\Delta R(j, \gamma) > 0.4, \Delta R(j, e) > 0.4$

Table 7–6 Overview of basic selection criteria for leptons, photons, and jets. These fundamental selections are independent of the specifics of the generator used and are essential for isolating stable particles and facilitating the analysis of complex event structures.

Variables	Cuts
N_{lep}	2 signal OSSF leptons with leading lepton $p_T^{\text{lep}} > 30 \text{ GeV}$
N_{pho}	1 signal photon with $p_T^\gamma > 35 \text{ GeV}$
N_{jet}	0
$\Delta R(\ell, \ell)$	< 3
$m_{\ell\ell}$	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$
$m_{\ell\ell} + m_{\ell\ell\gamma}$	$> 182 \text{ GeV}$

Table 7–7 Overview of event selection criteria employed in the analysis.

of the invariant mass of the lepton pair and the invariant mass of the lepton pair with the photon exceed twice of the Z boson mass ($m_{\ell\ell} + m_{\ell\ell\gamma} > 182 \text{ GeV}$). Additionally, a maximum separation between leptons, $\Delta R(\ell, \ell) < 3$, is applied to suppress SM non- $Z\gamma$ background contributions, as depicted in Fig. 7–6.

These selection criteria are pivotal for the accurate implementation of SMEFT and the Effective Vertex Function theory, facilitating precise analysis of the $e^+e^- \rightarrow Z(\ell^+\ell^-)\gamma$ process, where ℓ represents an electron or muon. The effectiveness of these event-topology based selections is demonstrated in Tables 7–8 - 7–9, which present the cutflow results and illustrate the impact of SM $Z\gamma$ contributions, new physics effects, as well as additional background

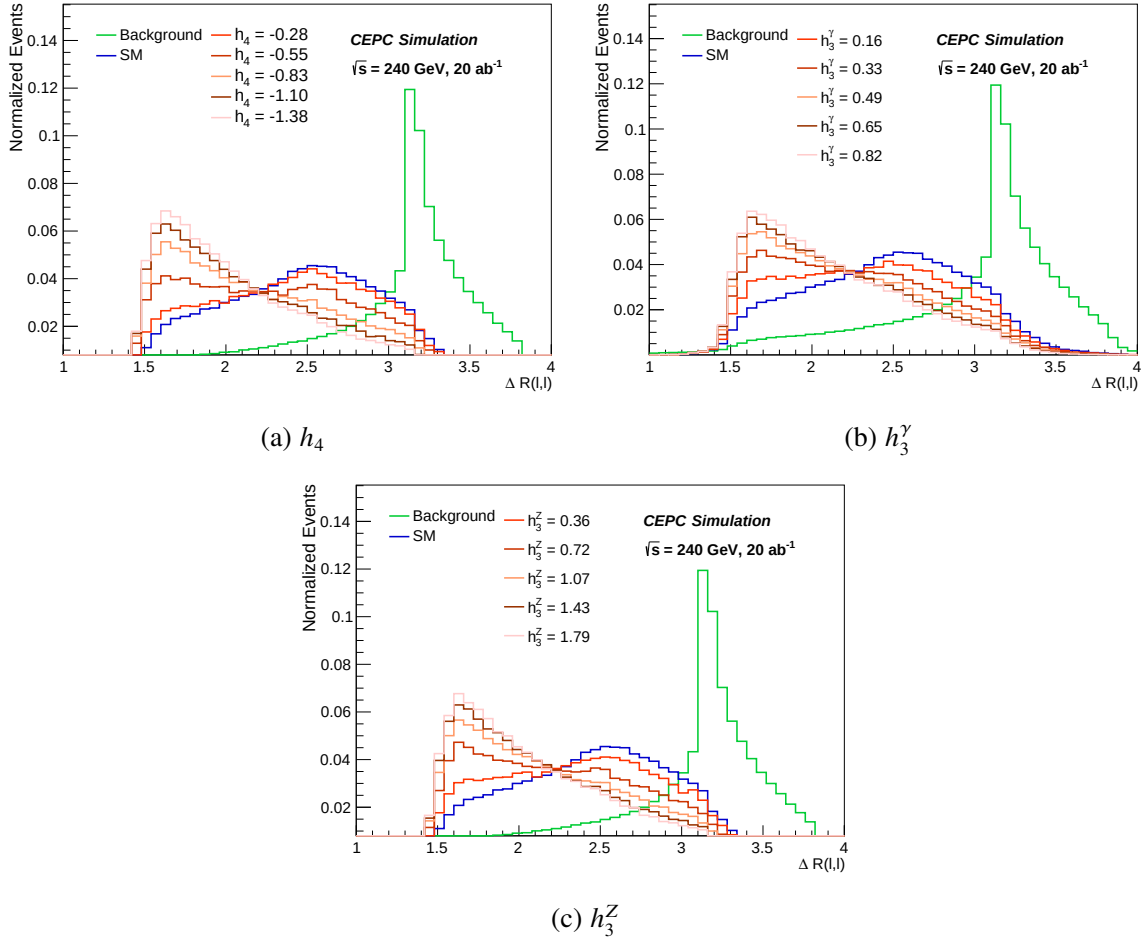


Figure 7–6 Normalized distributions of the lepton separation variable $\Delta R(\ell, \ell)$, accounting for the influence of nTGC form factors. The $\Delta R(\ell, \ell)$ distributions reveals notable variations in performance when comparing leptons from distinct sources. These variations are crucial in enhancing signal detection and effectively reducing background contributions.

processes.

7.3.2 Systematic Uncertainties

Systematic uncertainties play a pivotal role in shaping the precision of experimental measurements. These uncertainties are broadly classified into two principal categories: those associated with the signal and those related to background processes, each uniquely impacting the measurements reliability. Both systematic uncertainties have been assigned to the expected yields and then propagated to the EFT fits.

Variables	non- $Z\gamma$ Backgrounds	SM $Z\gamma$	h_4	h_3^γ	h_3^Z
$N_{\text{pho}} = 1$	11712	1572	1629	1747	1710
$N_{\text{lep}} = 2$	1152	587	624	696	675
$N_{\text{jet}} = 0$	811	587	624	696	675
$\Delta R(\ell, \ell) < 3$	698	548	585	656	634
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	303	192	226	288	271
$ m_{\ell\ell} + m_{\ell\ell\gamma} > 182 \text{ GeV}$	303	192	226	288	271

Table 7–8 Cutflow table for the nTGC form factors, showing cross sections (in [fb]) after applying sequential selections based on specified event-topology requirements. Initial cross sections for each nTGC form factors are detailed in Table 7–4. This strategy efficiently reduces SM background contributions while confirming the preservation of signal events.

Variables	non- $Z\gamma$ Backgrounds	SM $Z\gamma$	(h_4, h_3^γ)	(h_4, h_3^Z)	(h_3^γ, h_3^Z)
$N_{\text{pho}} = 1$	11712	1572	2614	2506	3811
$N_{\text{lep}} = 2$	1152	587	1225	1178	1999
$N_{\text{jet}} = 0$	811	587	1224	1176	1996
$\Delta R(\ell, \ell) < 3$	698	548	1179	1126	1929
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	303	192	751	717	1441
$ m_{\ell\ell} + m_{\ell\ell\gamma} > 182 \text{ GeV}$	303	192	751	717	1441

Table 7–9 Cutflow table for the nTGC form factors, showing cross sections (in [fb]) after applying sequential selections based on specified event-topology requirements. Initial cross sections for each nTGC form factors are detailed in Table 7–4. This strategy efficiently reduces SM background contributions while confirming the preservation of signal events.

Signal-Related Systematic Uncertainties At the CEPC, the influence of theoretical uncertainties on the signal measurements is relatively minimal due to the environment of the lepton collider, which significantly limits the impact of factors like Parton Distribution Functions (PDFs)^[237-238] and the strong coupling constant, α_s . For precise quantification, we adopt a conservative estimate of 0.5%^[239] for theoretical uncertainty related to the signal processes, mainly contribute to higher-order Quantum Chromodynamics (QCD) corrections.

Experimentally, the systematic uncertainties predominantly arise from several sources including integrated luminosity, the geometric configuration of the detector, and the efficiencies of trigger and identification algorithms. The luminosity is monitored using the high-precision Bhabha scattering^[240] method, achieving an accuracy of up to 0.1%^[239]. The detector simulation, based on a detailed geometric and operational model, ensures an exact-

ing control over the acceptance and response of the detector, and making these uncertainties negligible. Photon identification, reconstruction, and energy calibration are governed by dedicated defined algorithm^[36], with photon efficiency and energy scale uncertainties maintained within 1% and 0.05%, respectively. The estimation of lepton uncertainties involves varying the invariant mass window of the dilepton system by ± 1 GeV, allowing us to assess the impact of variations on the measurement accuracy directly related to the lepton isolation and identification criteris.

Background-Related Systematic Uncertainties Background uncertainties are handled by allowing for variations in the event yields estimates to account for potential mis-modelling and uncertainties in cross section calculations. The non- $Z\gamma$ background sources are categorized into three groups: dominant 2-fermion background process, non dominant 4-fermion and Higgs background processes. The dominant background processes of 2-fermion production are varied by 5% for reflecting the model precision, while yields from non-dominant background processes like 4-fermions or Higgs are varied by 100% to accommodate modelling discrepancies^[236].

Processes	Statistical	Theoretical	Experimental
$Z\gamma$ production ($e^+e^- \rightarrow \ell^+\ell^-\gamma$)	0.52%	0.5%	(+2.96, -3.15)%
Fixed background	Dominant background: 5%		
	Non-dominant background: 100%		

Table 7–10 Systematic uncertainties overview, delineates the systematic uncertainties assessed for the CEPC at a center-of-mass energy of $\sqrt{s} = 240$ GeV over an integrated luminosity of 20 ab^{-1} .

A comprehensive overview of the systematic uncertainties are listed in Table 7–10. Systematic uncertainties in signal processes are segregated into statistical, theoretical, and experimental categories. Predominantly, signal uncertainties arise from experimental aspects such as detector resolution, identification efficiencies, and detector acceptance, collectively termed "Experimental". For background uncertainties, variations are made dynamically to accommodate potential variability. These comprehensive categorizations and meticulous estimations of uncertainties are essential for refining the analytical precision at CEPC and ensuring that the experimental results are robust and reliable, effectively distinguishing between signal enhancements and potential background fluctuations.

7.4 Results and Discussions

The event yields for the SM $Z\gamma$ process and backgrounds are summarized in Table 7–11, following the implementation of comprehensive event-topology based selections. These yields are critical for evaluating the event topologies and propagated to the SMEFT framework incorporate all systematic uncertainties to enhance the precision in probing nTGCs.

Processes	Event Numbers ($\times 10^3$)
SM $Z\gamma$ Production	$3842.7^{117.1}_{124.2}$
2-fermion background	5965.1 ± 298.3
4-fermion background	8.0 ± 8.0
Higgs background	8.1 ± 8.1
Total yields	$9823.8^{+320.7}_{-323.3}$

Table 7–11 Expected yields of SM events and associated uncertainties [10^3] extracted under the center-of-mass energy of $\sqrt{s} = 240$ GeV with integrated luminosity of 20 ab^{-1} . These yields account for both electron and muon channels, and incorporate the full consideration of statistical and systematic uncertainties, following the employment of all event-topology-based selection criteria.

In this study, a binned profile-likelihood approach is employed to derive upper limits on Wilson coefficients for dimension-8 operators at 95% Confidence Level (C.L.) using the EFT-fun^[241] fitting framework. Both one-dimensional and two-dimensional limits on nTGC parameters are set individually and within the parameter planes to demonstrate the correlations. The systematic uncertainties, including both statistical and systematic components as delineated in Section 7.3, are thoroughly incorporated into the EFT-fun framework for the extraction of exclusive limits. Kinematic variables ϕ and θ , as depicted in Fig. 7–4, are pivotal in differentiating between SM contributions and potential nTGC effects beyond the SM. These variables are instrumental in enhancing the sensitivity to nTGC coefficients and form factors, crucial for refining the theoretical understanding of electroweak interactions.

Table 7–12 presents the derived exclusive constraints for the new physics scale Λ_i , based on the expected limits on the nTGC form factors from the SMEFT dimension-8 coefficients given in the Effective Vertex Approach in Eq. 7–4, with all sources of uncertainties taken into account.

The constraints on the form factors from the Effective Vertex Approach are illustrated in Fig. 7–7, and Fig. 7–8 presents the corresponding limits on the operator scales with the

Form Factors	Expected Limits	New Physics Scales	Expected Limits [TeV ⁻⁴]
h_4	$[-2.0 \times 10^{-4}, 2.0 \times 10^{-4}]$	Λ_{G+}	1.55
h_3^γ	$[-9.7 \times 10^{-4}, 9.7 \times 10^{-4}]$	Λ_{G-}	0.76
h_3^Z	$[-1.1 \times 10^{-3}, 1.1 \times 10^{-3}]$	$\Lambda_{\widetilde{B}W}$	0.85
		$\Lambda_{\widetilde{B}\widetilde{W}}$	1.05

Table 7–12 Exclusive constraints for both the new physics scales Λ_j , and the form factors h_4, h_3^γ, h_3^Z at 95% C.L. These limits are derived and extracted through the reaction of $e^+e^- \rightarrow Z\gamma$ process under the center-of-mass energy of $\sqrt{s} = 240$ GeV and a benchmark integrated luminosity of 20 ab^{-1} .

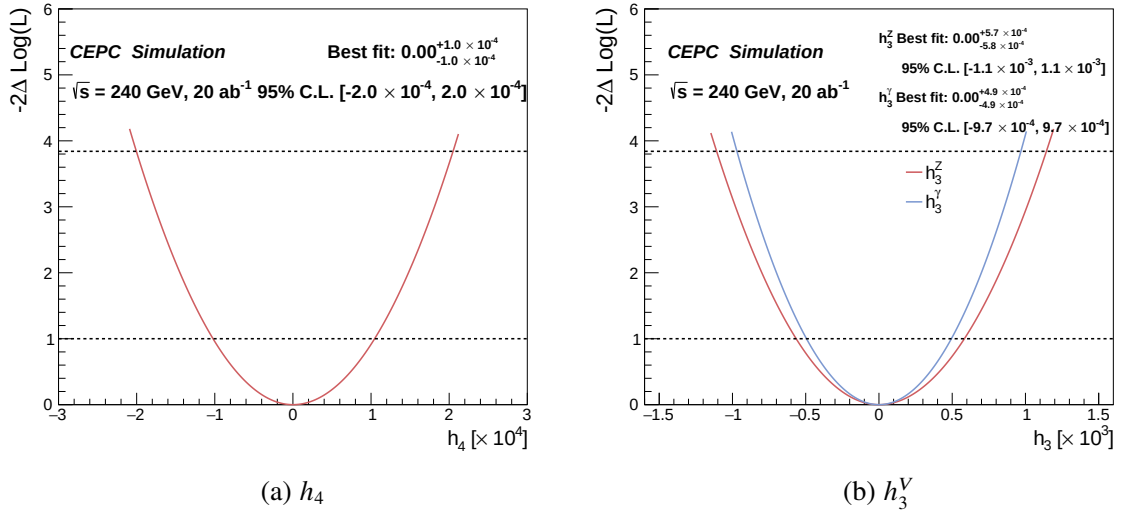


Figure 7–7 The expected limits at 95% C.L. on the nTGC form factors h_4, h_3^γ , and h_3^Z . The best fit values showcased in the graphs align closely with the SM predictions.

SMEFT framework. Both figures demonstrate the central 95% C.L. range of the likelihood distribution, excluding values outside this interval. These visual representations show the expected constraints on both the form factors and dimension-8 operator coefficients within the SMEFT framework, providing a thorough understanding of the sensitivities to these higher-dimensional operators.

In addition to one-dimensional limits, the study also explores constraints on pairs of nTGC parameters to examine the correlations. These correlations are visually represented through two-dimensional contour plots, as shown in Fig. 7–9. The solid lines in these plots mark the experimental constraints at the 68% C.L., while the dashed lines indicate the exclu-

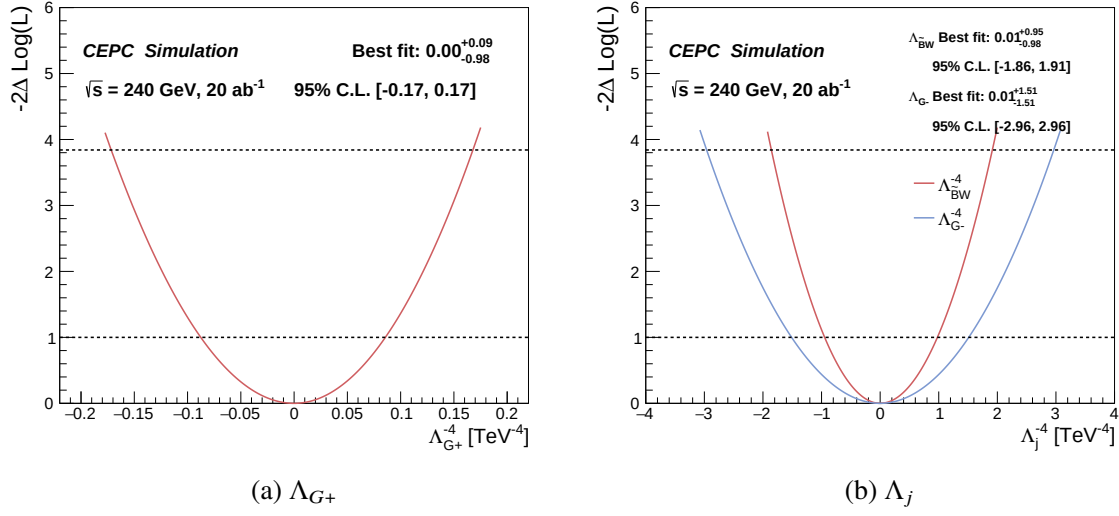


Figure 7–8 The expected limits at 95% C.L. on the nTGC form factors Λ_{G+} , Λ_{G-} , and $\Lambda_{\tilde{B}W}$. The best fit values showcased in the graphs align closely with the SM predictions.

sion limits at the 95% C.L.

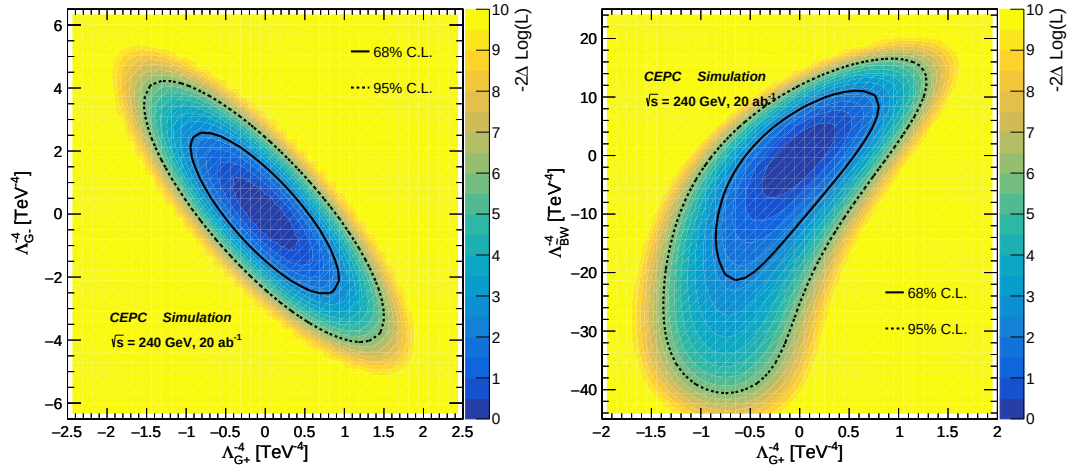


Figure 7–9 Contour plots at the 68% and 95% C.L. for cutoff scales Λ_j for each pair of dimension-8 nTGC operators, with axis unit in $[\text{TeV}^{-4}]$.

Furthermore, the constraints derived from these analyses are transformed into limits on the new physics scales of dimension-8 SMEFT operators, as displayed in Fig. 7–10.

These constraints are determined after considering all systematic uncertainties, which highlights significant correlations between pairs of nTGC parameters. The elliptical contours in both figures demonstrate the correlation between different nTGC parameters, providing a

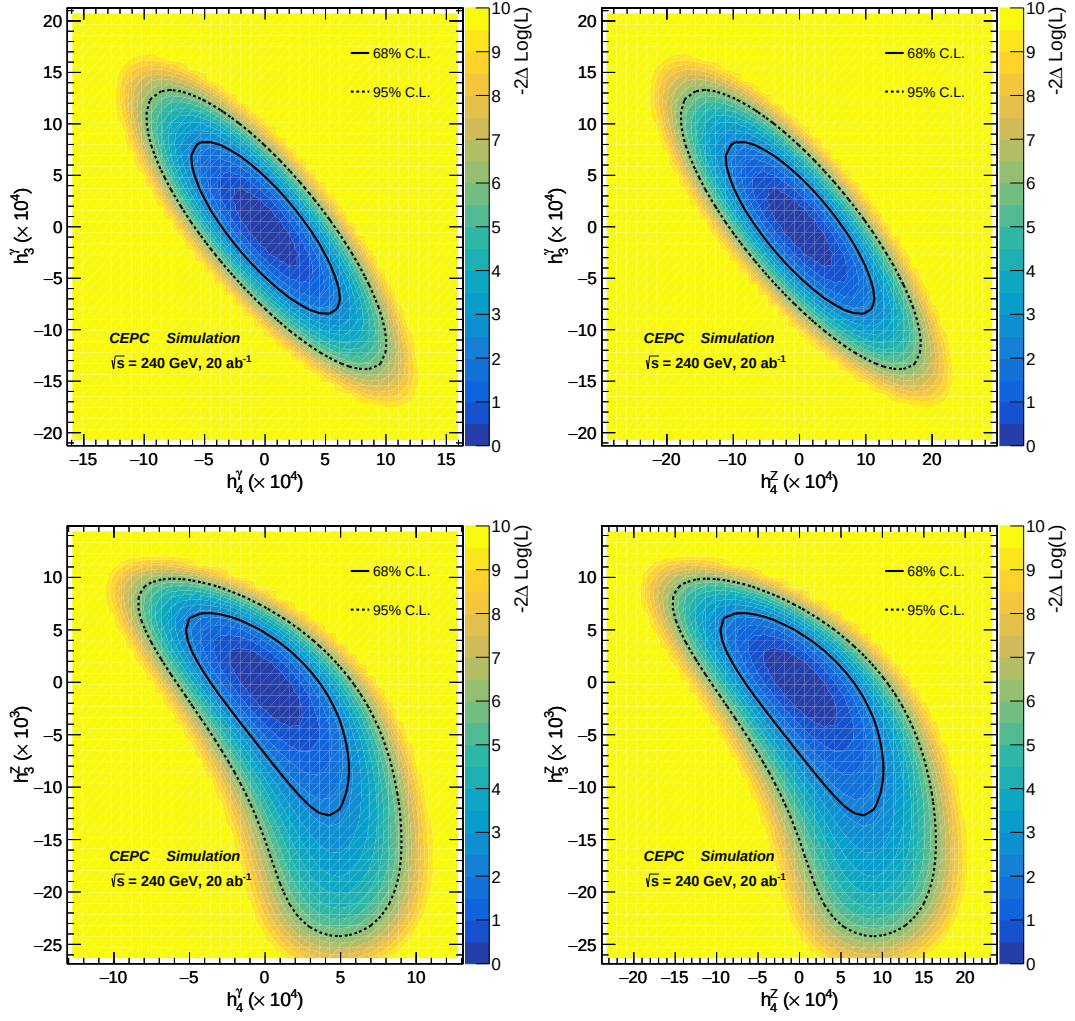


Figure 7-10 Contour plots at the 68% and 95% C.L. for each nTGC form factor pair.

comprehensive overview of the sensitivities reaches to individual higher-dimensional operators within the SMEFT framework.

7.5 Conclusion

The investigation of neutral triple gauge couplings (nTGCs) via dimension-8 operators provides a critical method for probing physics beyond the Standard Model (SM). These vertices, such as $Z\gamma V^*$, do not emerge within the dimension-4 SM Lagrangian nor under dimension-6 enhancements, marking them as unique probes at the dimension-8 level. This study extracts the sensitivity to nTGCs through the reaction $e^+e^- \rightarrow \ell^+\ell^-\gamma$ (where ℓ de-

notes electrons or muons), employed with detector-level simulations at the Circular Electron Positron Collider (CEPC).

Previous studies into the $Z\gamma V^*$ vertex using nTGC form factors^[10] are not consistent with the spontaneously-broken electroweak gauge symmetry of the SM. A revised theoretical framework^[13-14] has been established, linking a comprehensive set of dimension-8 nTGC operators within the Standard Model Effective Field Theory (SMEFT). This framework utilized the full electroweak symmetry, necessitating the relationship of additional dimension-8 operators to accurately map nTGC form factors. In this analysis, a novel nTGC form factor formulation has been applied through $Z\gamma$ channel. Utilizing a realistic detector configuration, we conducted a thorough simulation incorporating both systematic and statistical uncertainties. By adopting a cut-based analytical approach, enhanced with the Boosted Decision Tree Gradient (BDTG) technique, the ability to differentiate between positive and negative interference events has been significantly enhanced compare with traditional strategy, thus improving the overall detection sensitivity.

The results demonstrate that nTGC measurements at the CEPC, and potentially other future e^+e^- collider projects, could extend the exploration of new physics to energy scales well beyond the traditional reach of collider experiments, up to several teraelectronvolts. These findings highlight the capability of nTGCs to offer insights into new physics territories, thereby extending the utility of the SMEFT framework well into higher dimensions beyond the dimension-6 analysis.

Chapter 8 Summary and Future Prospects

In this concluding chapter of this dissertation, it is interesting to reflect on the fundamental theories and questions that have driven this multifaceted research. The Standard Model (SM) of particle physics forms the theoretical backbone for understanding the elementary interactions mediated by gauge bosons : electroweak, weak, and strong forces. This framework categorizes elementary particles into fermions and bosons, which underpin the structure of the universe. Despite extensive empirical validation, the Standard Model still presents unresolved questions that demand further investigation. Specifically, this dissertation concentrates on the dynamics of gauge boson interactions, with a particular emphasis on $Z\gamma$ production. This focus area serves as a platform for validating the Standard Model predictions and for probing potential new phenomena that may reside beyond the established theoretical landscape.

$Z\gamma$ production provides a valuable pathway for testing the Standard Model (SM) and probing potential new physics through the clean experimental signature, particularly when the Z boson decays into charged leptons (electron or muon). This clarity facilitates precise measurements and reduced background contributions, making it an excellent channel for verifying SM predictions and exploring deviations that could indicate new physics, such as anomalous triple gauge couplings (aTGCs). Moreover, studying the $Z\gamma$ production offers direct insights into electroweak interactions and can reveal deviations in transverse momentum and angular distributions, suggesting the presence of new particles or interactions beyond the SM, thereby helping refine our understanding of fundamental particle interactions and potentially uncovering novel phenomena within and beyond the electroweak scale.

This dissertation firstly focuses on the detailed study of $Z\gamma$ production in association with jet activities at the Large Hadron Collider (LHC), analyzing data from the ATLAS detector across a total integrated luminosity of 139 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 13\text{ TeV}$. The core objective is to conduct precision measurements of various differential distributions, particularly where the Z boson decays into two opposite sign, same flavor leptons (electron or muon), providing a clear final state with high resolution. The research aims to advance our understanding of the Standard Model (SM) and explore potential new physics beyond the SM by probing sensitivities to hadronic activity through quantum chromodynamics (QCD)

radiation. These measurements to jet activity are essential for fitting SM parameters and calibrating models using various kinematic observables, including parton distribution functions and predictions, incorporating resummation of Sudakov logarithms.

Methodologically, the results of this study are compared with both Monte Carlo (MC) predictions and fixed-order calculations like MATRIX, with additional insights from recent results incorporating MiNNLO_{PS} . The analysis includes both one-dimensional and two-dimensional distributions, covering variables inclusive jet multiplicity and jet-related observables. It is noted that while some models, such as MADGRAPH, show good agreement in terms of shapes and total yields, SHERPA NLO (2.2.11) and LO (2.2.4) generally underpredict the data, with NLO predictions being more accurate than LO. The results from this comprehensive analysis provide critical insights into the verification of SM predictions and explore potential Beyond the Standard Model (BSM) effects, particularly in areas dominated by resummation calculations. These findings are instrumental in constraining QCD predictions and enhancing our understanding of BSM predictions, including effective field theory (EFT) models or Axion-Like Particles (ALPs). By detailing the kinematic distributions and their deviations, this research significantly contributes to the field, offering potential pathways for new physics explorations and refining our understanding of fundamental particle interactions.

Building upon the previous study, this dissertation then provides an extensive analysis of $Z\gamma$ production, with a focus on precision measurements and exploring new physics beyond the Standard Model (SM) using data collected by the ATLAS detector at the LHC from 2015 to 2018. The dataset, representing an integrated luminosity of approximately 140 fb^{-1} at a center-of-mass energy of 13 TeV, allows for detailed study of fiducial cross section measurements of $Z\gamma$ events optimized for EFT interpretation, where Z boson decays into leptonic pairs of electrons and muons with opposite signs. Key to this analysis is the application of the Standard Model Effective Vertex Field Theory (SMEFT) to probe neutral Triple Gauge Couplings (nTGCs) that emerge uniquely at dimension-8 within the SMEFT framework. This study involves precise measurements of the photon transverse momentum and the differential distributions crucial for applying the SMEFT in both one-dimensional and two-dimensional limits. This approach incorporates novel, fully gauge-invariant treatments of additional dimension-8 operators (O_{G+} and O_{G-}), alongside traditional dimension-8 opera-

tors, facilitating a deeper exploration into electroweak interactions and the potential discovery of phenomena beyond the Standard Model.

The analysis marks a pioneering achievement as it presents the first empirical results employing the latest nTGC formulation, contributing significantly to our understanding of gauge boson interactions at high energy scales. It also tests the robustness of the SM under these conditions, enhancing detection sensitivity for potential new physics and providing the most recent experimental constraints on dimension-8 operators, as well as bounds on form factors from effective vertex function. These results not only reinforce the predictive power of the SM but also open new avenues for exploring BSM phenomena through the advanced theoretical and methodological frameworks employed in this comprehensive study.

Looking beyond the analyses performed at the Large Hadron Collider (LHC), this research extended into studies at future lepton colliders to explore neutral Triple Gauge Couplings (nTGCs) via dimension-8 operators. The transition from hadron to lepton collider, such as the Circular Electron Positron Collider (CEPC), allows for a more controlled and precise examination of electroweak interactions and potential new physics phenomena. This dissertation also extended the focus on the dimension-8 nTGC at lepton collider, which do not manifest within the dimension-4 Standard Model Lagrangian nor dimension-6 level. These higher-dimensional operators provide unique insights into high energy interactions, potentially uncovering new dynamics and particles that lie beyond the current scope of the SM. This study also focuses on exploring nTGCs through $Z\gamma$ production with fully leptonic decays.

Utilizing simulated data from CEPC, this research employs comprehensive simulations to map nTGC form factors accurately. This approach not only facilitates the study of $Z\gamma$ production through realistic detector configurations and cut-based analytical methods but also enhances detection sensitivity by utilizing advanced techniques such as the Boosted Decision Tree with Gradient (BDTG). These efforts have significantly improved the ability to differentiate between potential signal and background contributions, refining the overall quality and reliability of the experimental results. The results from these studies at the CEPC and the integration of the latest theoretical developments in SMEFT underscore the potential nTGCs to extend our exploration of new physics to energy scales well beyond traditional collider experiments, reaching into several TeV.

During my Ph.D., my doctoral research combines theoretical exploration with experimental precision, significantly advancing our understanding in three critical areas of particle physics. I have refined the precision measurements of $Z\gamma$ production at the Large Hadron Collider (LHC), delving deep into the realm of neutral Triple Gauge Couplings (nTGCs) through dimension-8 operators and extending these studies into both hadron and lepton colliders. This progression provides some discrimination between SM predictions and also challenges existing boundaries about high energy particle interactions. My research integrates advanced data analysis with robust theoretical and experimental techniques, forstering a conducive environment for potential groundbreaking discoveries in understanding the fundamental constituents of the universe.

In my continuing journey at the LHC, my research into multi-boson production and BSM phenomena is set to expand with the advent of Run 3 data-taking of LHC. This forthcoming phase will not only bolster the statistical power of my researches but also enhance the precision of our investigations into phenomena such as electroweak boson polarization and anomalous couplings. I am deeply committed to dedicating my efforts towards exploring new frontier in collider physics, continually seeking to expand the boundaries of our understanding through innovative research and pioneering experimentation.

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Acknowledgements

Reflecting on the past five years, I am deeply grateful for the period that, though brief, was rich with growth and discovery. These years have been more than just a chapter in my life, they have been a pivotal period that solidified my dedication to physics. I was fortunate to have the unwavering support and invaluable guidance of my supervisor, family, colleagues, and friends. I am profoundly thankful for the encouragement that fueled my passion and the critical insights that deepened my understanding of the universe. It is a privilege to acknowledge the significant contributions of those who have been instrumental during my Ph.D. journey.

First of all, I wish to express my deepest gratitude to my supervisor, Prof. Shu Li, who opened the door for me to join the ATLAS collaboration. Under his guidance, I was provided numerous opportunities to work, grow, and refine my skills, which trained me into a qualified researcher. Beyond the professional mentorship, Prof. Li has shown remarkable care for my life, teaching me not only the nuances of the profession in an academic career but also the importance of maintaining a positive attitude and resilience. He personally tutored me in coding during my qualification task and was always there to support me during family emergencies. His proactive planning ensured that all projects progressed smoothly and on time. His wisdom and guidance are treasures that will enrich my life forever.

I would also like to acknowledge my family, my parents and my brother, who have supported and trusted me throughout the journey. No matter where I was or what challenges I faced, their boundless love and care surrounded me. I am deeply grateful for their belief in my abilities and their sacrifices to my growth. The comfort and encouragement they provided are crucial to my career as any academic support. Thank you for being my constant source of strength, love, and inspiration. Please continue to be proud of me.

My appreciation extends to my colleagues from the ATLAS group of Shanghai Jiao Tong University and Tsung-Dao Lee Institute. Prof. Kun Liu, in particular, has provided invaluable support. Without his guidance and discussion, my research could not have been successful. I am also grateful to Yifan Zhu, Dr. Yulei Zhang, Qiuping Shen, Qibin Liu, Zhen Wang, Xiang Chen, and Xi Wang for their collaborative spirit and friendship which bolstered both my work and personal life. Yifan is such a good friend that has always been a strong support

both in research and life, while Yulei has generously shared advanced techniques and resolved numerous challenges of my life. Furthermore, my sincere thanks go to all my collaborators, Dr. Rui-Qing Xiao, Dr. Lorenzo Rossini, Dr. Xuan Yang, and Dr. Rui Yuan, all of them have enriched my research experience, helping me become a seasoned researcher with theoretical and experimental skills. Their contributions have been instrumental in achieving the fruitful publications in our joint efforts. Each of you contributed not only to my professional knowledge but also to my personal growth. Your shared insights, spirited discussions, and constructive feedback have greatly enriched my research experience.

I am profoundly grateful to my friends, Siyu Duan, Shuhui Huang, Ruoshi Jiang, Cheng Jin, Sami Kaci, Rummann Bin Amir, Guanming Huang, and Kang Liu, LinYang who have been my endless source of support. They celebrated my achievements and stood by me during challenging times, helping me navigate the digest negative emotions. Their encouragement and genuine happiness for my successes have been treasured. I am the luckiest one who have such understanding and supportive friends. Thank you for being there every step of the way.

Last but not lest, I especially want to express my great appreciation to Prof. John Ellis, Prof. Jonathan Butterworth, Prof. Dave Charlton, Prof. Hong-Jian He, Prof. Qiang Li, Prof. Zhijun Liang, and Prof. Hongtao Yang. All of them took time from their intensive schedules to attend my defense. The presence and detailed examination of my thesis have been invaluable. The constructive feedback and insightful comments provided have not only refined my work but also enriched my academic journey. Thank you for your commitment and invaluable contributions to my academic career development.

List of Research Achievements

First-Author Publications

1. **Danning Liu**, Rui-Qing Xiao, Shu Li, John Ellis, Hong-Jian He, Rui Yuan. Probing Neutral Triple Gauge Couplings via $Z\gamma(\ell^+\ell^-\gamma)$ Production at e^+e^- Colliders. arXiv:2404.15937, Front.Phys.20(1),015201(2025), doi: 10.15302/frontphys.2025.015201 (**Cover Story Highlight**)

ATLAS Collaboration Publications with my major contributions

1. **ATLAS Collaboration** Measurement of the $Z\gamma$ +jets differential cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. arXiv:2202.07184, JHEP 07 (2023) 72 (**ATLAS Internal Note Editor**, Standard Model Plenary **Approval Talk**)

ATLAS Collaboration Conference Notes

1. **ATLAS Collaboration** Measurement of the electroweak production of $Z\gamma$ using 139 fb^{-1} of 13 TeV pp collision data with the ATLAS detector. ATLAS-CONF-2021-038
2. **ATLAS Collaboration** Measurement of the $Z\gamma$ +jets differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. ATLAS-CONF-2022-047
3. **ATLAS Collaboration** $Z(\rightarrow \ell\ell)\gamma$ anomalous neutral triple gauge coupling analysis with 140 fb^{-1} Run2 data. ANA-STDM-2023-06 (aiming for ATLAS CONF Note, **Contact Editor**)

Co-Author Publications

1. Y. Duan, ..., D. Liu, ..., et al. Scintillator Tile Batch Test of CEPC AHCAL. arXiv:2111.03660 (JINST 17 (2022) 05, P05006)
2. J. Chen, ..., D. Liu, ..., et al. Prospective study of light dark matter search with a newly proposed DarkSHINE experiment. Sci. China Phys. Mech. Astron. 66, 211062 (2023)

3. Z. Zhao, ..., D. Liu, ..., et al. Design of a LYSO Crystal Electromagnetic Calorimeter for DarkSHINE Experiment. arXiv:2407.17800 (Submitted to Nuclear Science and Techniques)

Proceedings

1. **Danning Liu**, Shu Li. Measurements of the integrated and differential cross sections of $Z(\rightarrow \ell\ell)\gamma$ production and probe for neutral triple gauge couplings. (NPPP 346 (2024) 6, doi: 10.1016/j.nuclphysbps.2024.06.012)

Selected International Conference Talks

1. 2023: The study of nTGCs in Z+photon at the CEPC. **Parallel Talk @ The 2023 International Workshop on the High Energy Circular Electron Positron Collider.** Nanjing, China
2. 2023: Measurement of electroweak gauge boson production in association with jets at ATLAS. **Parallel Talk @ 34th Rencontres de Blois on "Particle Physics and Cosmology".** Blois, France
3. 2022: Precise measurement of $Z\gamma$ +jets and EFT interpretation with ATLAS Full Run-2. **Plenary Talk @ Multi-Boson Interaction.** Shanghai, China
4. 2022: Precise measurement of Z+photon final states and search for nTGCs with EFT at ATLAS. **Plenary Talk @ TDLI-PKU BSM workshop : Electroweak lights the way.** Shanghai, China

Selected Domestic Conference Talks

1. 2024: Probing Neutral Triple Gauge Couplings via $Z\gamma(\ell^+\ell^-\gamma)$ Production at e^+e^- Colliders. **Plenary Talk @ CEPC New Physics Workshop.** Zhengzhou, China
2. 2024: Probing Neutral Triple Gauge Couplings via $Z\gamma(\ell^+\ell^-\gamma)$ Production at e^+e^- Colliders. **Parallel Talk @ High Energy Physics Annual Workshop.** Qingdao, China
3. 2023: Precise measurement of SM-EWK $Z\gamma$ +jets and constraints on neutral triple gauge couplings at ATLAS and future collider with EFT approach. **Parallel Talk @**

The 17th TeV Physics Workshop. Nanjing, China

4. 2023: Precise measurement of $Z(\rightarrow \ell\ell)\gamma$ final states and search for neutral triple gauge couplings. **Parallel Talk @ The 9th China LHC Physics Workshop.** Shanghai, China
5. 2022: Precise measurement of Z+photon final states and search for nTGCs with EFT at ATLAS. **Parallel Talk @ High Energy Physics Annual Workshop.** Dalian, China
6. 2022: Precise measurement of $Z\gamma$ final states and search for nTGCs with EFT at ATLAS. **Parallel Talk @ The 3rd Frontier in Particle Physics Workshop.** Guangzhou, China
7. 2021: Diboson simulation and precise measurement of $Z\gamma$ analysis in ATLAS detector. **Poster @ High Energy Physics Annual Workshop.** Qingdao, China
8. 2021: Diboson process modelling with FxFx merging at ATLAS **Parallel Talk @ The 7th China LHC Physics Workshop.** Nanjing, China

Invited Talk

1. 2022: Precise measurement of Z+photon final states, Polarization and Search for nTGCs with EFT at ATLAS. **SYSU-PKU Collider Physics Forum For Young Scientists**

ATLAS Collaboration Approval Talks

1. 2022: $Z\gamma$ +jets SM Approval Talk. Presented at the Standard Model Plenary Meeting

Honors, Prizes, and Academic Appointments

1. 2023-present : Contact Editor of ATLAS $Z(\rightarrow \ell\ell)\gamma$ nTGC analysis
2. 2020-2023 : $Z\gamma$ +jets paper Internal Note Editor
3. 2023 : Outstanding Student Scholarship of the Key Laboratory - Ministry of Education, China
4. 2023 : China Guanggu Scholarship
5. 2021 : Guanghua Scholarship

Outreach Events

1. 2024: Ph.D. student Representative and Lightening Talk for ATLAS Collaboration Management Delegation visit to Tsung-Dao Lee Institute, Shanghai Jiao Tong University.
2. 2023: Designer of Collider Physics History and Culture Wall (Outreach Style) for SJTU SPA-INPAC/TDLI-Production.
3. 2022: One of the Six Representative for ATLAS Collaboration (~ 6000 members) @ International Day of Women and Girls in Science.