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**Detoured and Delayed: Delving into the Depths of Displaced
Vertices**

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Vertices**

by

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वो लोहा था, पिघल गया
खिचा-खिचा मचल गया
सितार में बदल गया

I dedicate this to my family, and my love Lekha.

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Abstract

Detoured and Delayed: Delving into the Depths of Displaced Vertices

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This thesis presents a search for displaced production of Higgs bosons or Z^0 bosons, originating from the decay of a neutral long-lived particle (LLP) and reconstructed in the decay modes $H \rightarrow \gamma\gamma$ and $Z \rightarrow ee$. The thesis uses the full Run 2 data set of proton–proton collisions delivered by the LHC at an energy of $\sqrt{s} = 13$ TeV between 2015 and 2018, and recorded by the ATLAS detector, corresponding to an integrated luminosity of 139 fb^{-1} . Exploiting the capabilities of the ATLAS liquid argon (LAr) calorimeter to precisely measure the arrival times and trajectories of electromagnetic objects, we search for the signature of pairs of photons or electrons which arise from a common displaced vertex and which arrive after some delay at the calorimeter. The results are interpreted in a gauge-mediated supersymmetry breaking model where the LLPs are pair-produced and each LLP subsequently decays into either a Higgs boson or a Z^0 boson. The final state includes a particle that escapes detection, giving rise to missing transverse momentum. No significant excess is observed above the background expectation. The results are used to set upper limits on the cross section for the LLP pair-production, for signals with an LLP mass between 100 and 705 GeV and lifetime between 0.25 and 1000 ns. A model-independent limit is also set on the production of pairs of photons or electrons with a significant delay of arrival at the calorimeter.

Table of Contents

Acknowledgments	5
Abstract	7
List of Tables	12
List of Figures	14
Chapter 1 Introduction	19
Chapter 2 The Standard Model and Beyond	22
2.1 The Standard Model of Particle Physics.....	22
2.1.1 Standard Model	22
2.2 ... and Beyond	25
2.2.1 Naturalness of the Higgs Boson Mass	25
2.2.2 Gravity.....	26
2.2.3 Dark Matter and Dark Energy	27
2.2.4 Matter-Antimatter Asymmetry.....	27
Chapter 3 Supersymmetry	28
3.1 Introduction	28
3.2 Minimal Supersymmetric Standard Model.....	29
3.3 SUSY is a broken symmetry?	32
3.4 Gauge Mediated Supersymmetry Breaking.....	35
3.5 Long-lived particles	35
3.6 Displaced and delayed electromagnetic objects.....	38
3.7 Previous search results.....	42
3.8 Summary	43
Chapter 4 The Large Hadron Collider	45
4.1 Concepts of Accelerator Physics	45
4.2 The Large Hadron Collider	48
4.3 Operating Conditions in Run 2	52

Chapter 5 The ATLAS Experiment	55
5.1 Overview of the ATLAS Detector	55
5.2 Inner Detector	58
5.3 Calorimetry	61
5.3.1 Liquid Argon Calorimeter	61
5.3.2 LAr Calorimeter Readout	66
5.3.3 Energy and Time Reconstruction	68
5.3.4 Tile Calorimeter	69
5.4 Muon Spectrometer	70
5.5 Magnet System.....	72
5.6 Forward Detectors	73
5.7 Trigger and Data Acquisition.....	74
Chapter 6 Physics Object Identification and Reconstruction	77
6.1 Track and Vertex Reconstruction.....	78
6.1.1 Primary Vertex Identification.....	78
6.1.2 Track Reconstruction	79
6.2 Physics Object Reconstruction	84
6.2.1 Topological Clustering.....	84
6.2.2 Photons and Electrons	90
6.2.3 Jets	106
6.2.4 Muons.....	108
6.2.5 Missing Transverse Energy	111
6.2.6 Overlap Removal.....	115
Chapter 7 Data and Simulated Events	116
7.1 Data.....	116
7.1.1 Event Preselection.....	117
7.1.2 Trigger	117
7.2 Monte Carlo Simulation.....	118
7.3 Simulated Signal Samples	120
Chapter 8 Calorimeter Timing and Vertexing	122
8.1 Timing Calibration	123

8.1.1	Event Selection	124
8.1.2	Calculation of Calibration Constants.....	126
8.1.3	Timing Performance	134
8.1.4	Smearing in Simulation	135
8.1.5	Satellite Collisions	135
8.2	Trackless Calo-Vertexing.....	137
8.2.1	Photon Pointing.....	137
8.2.2	Pointing Resolution	139
8.2.3	Calo-Vertexing	140
8.2.4	Vertexing Resolution.....	142
Chapter 9	Analysis Strategy	147
9.1	Event Selection.....	147
9.1.1	Photon Object Selection	147
9.2	Analysis Region Definitions.....	152
9.2.1	Summary of Analysis Regions.....	154
9.3	Sensitive Variables	157
Chapter 10	Background Estimation	164
10.1	Purity Scaling.....	165
10.2	$E_{\text{cell}}^{\text{maxE}}$ Reweighting	165
10.3	Residual Timing Shift.....	166
Chapter 11	Systematic Uncertainties	169
11.1	Background Uncertainties.....	169
11.1.1	Photon Purity Fraction	170
11.1.2	$E_{\text{cell}}^{\text{maxE}}$ Reweighting	171
11.1.3	Pileup profile extrapolation	172
11.2	Signal Uncertainties	173
11.2.1	Integrated Luminosity Uncertainty	174
11.2.2	Detector Uncertainties	174
11.2.3	Theory Uncertainties	176
11.2.4	Timing Resolution Uncertainty.....	176
Chapter 12	Statistical Analysis	179

12.1 Statistical Analysis Concepts	179
12.1.1 Hypothesis Testing	179
12.1.2 Can one event be a discovery?	180
12.1.3 No signal, but exclusion!	182
12.1.4 Likelihood Function and Profile Likelihood Ratio	183
12.2 Fit Implementation	184
12.3 Fit Validation	185
12.3.1 Validation of Fit Procedure	185
12.3.2 Validation of Background Model	186
Chapter 13 Results and Interpretation	191
13.1 Unblinded Signal Region Results	191
13.2 Limits and Exclusion	195
13.3 Model-Independent Result	200
Chapter 14 Conclusion	202
Appendices	205
Chapter A Satellite Collisions	206
Chapter B Timing Investigations	212
B.1 Timing Distributions Across Timing Quadrants	212
B.2 Timing Variable Candidates	213
B.3 Lifetime Reweighting	214
B.4 Timing Resolutions	217
Bibliography	219
Vita	239

List of Tables

3.1	Chiral and gauge supermultiplets in the Minimal Supersymmetric Standard Model (MSSM)	31
3.2	Particle content of the MSSM.	34
5.1	General performance goals of the ATLAS detector. Note that, for high p_T muons, the muon-spectrometer performance is independent of the inner-detector system. The units for E and p_T are in GeV.	58
5.2	Granularity in $\Delta\eta \times \Delta\phi$ of the EM cells [1].	65
5.3	Main parameters of the sub-detectors of muon spectrometer [2].	70
6.1	Quality criteria used to select tracks for vertex finding. Si refers to the pixel or SCT detectors.	78
6.2	Quality criteria used in the ambiguity solver. Si refers to the combined pixel and SCT systems. $ d_0^{BL} $ and $ z_0^{BL} $ are the impact parameters calculated with respect to the beamline (BL) [3].	83
6.3	Parameters used to build the two types of the topological cluster available in the standard ATLAS reconstruction.	85
6.4	Description of the geometric topo-cluster moments, ϕ_{clus}, η_{clus}	89
6.5	Description of the signal topo-moments.	89
6.6	Discriminating variables used for photon identification.	99
6.7	Definition of the electron isolation working points. In the Gradient working point definition, the unit of p_T is GeV. All working points use a cone size of $\Delta R = 0.2$ for calorimeter isolation and $\Delta R_{max} = 0.2$ for track isolation [4].	103
6.8	Definition of the photon isolation working points [4].	103
7.1	Signal grid of the long-lived $\tilde{\chi}_1^0$ signal models	121
8.1	Electron candidate quality cuts	124

8.2	Number of electron candidates in the $W \rightarrow e\nu$ and $Z \rightarrow ee$ samples, broken down according to whether they are in the EMB or EMEC calorimeter, and according to the gain used to digitize the second-layer cell used in the timing analysis.	125
8.3	Electron object selections for $Z \rightarrow ee$ events	143
9.1	Photon object selections	152
9.2	Event-level selections for the analysis regions and their corresponding Run 2 data yields	157
9.3	Summary of the preselection, event-level selection, and analysis regions	163
11.1	Breakdown of the detector uncertainties	175
11.2	Breakdown of the theoretical uncertainties for two signal models	176
12.1	Distribution of p_0 -values and spurious signal significance for VR fits .	187
12.2	Expected and observed number of background events in the analysis VRs.....	188
13.1	Selection of the photon candidates for the model-independent results.	201
13.2	Results for the model-independent analysis	201
A.1	Predicted and measured number of satellite collision events across the analysis regions.....	206
A.2	Event- and object-level characteristics of the signal region event in the highest timing and vertexing bin	207

List of Figures

2.1	Particle content of the Standard Model [5].	23
3.1	Artistic representation of the SM and SUSY particles	29
3.2	Distribution of the various long-lived particles in the SM	36
3.3	Illustration of the signature of a displaced vertex	39
3.4	Feynman diagrams for the signature of the signal process of the considered GMSB model.	41
3.5	Production cross section calculation for pure Higgsino-like pair production	42
3.6	Distributions of the transverse momentum (p_T) and relativistic speed (β) of the NLSP for several values of the NLSP mass	43
4.1	Schematic layout of the LHC with its 8 arc sections, two-beam design, and its four experimental insertions [6].	49
4.2	Schematic of the CERN accelerator complex and the relative positions of the experiments.	50
4.3	Various phases of the LHC operation	51
4.4	Cumulative luminosity versus time	53
4.5	Luminosity-weighted distribution of the mean number of interactions per crossing for the 2015–2018 pp collision data at 13 TeV center-of-mass energy	54
5.1	Cut-away view of the ATLAS detector [7].	56
5.2	Illustration of the ATLAS coordinate system with a cylindrical detector.	57
5.3	Cut-away view of the ATLAS Inner Detector	59
5.4	Cut away of the ATLAS calorimeter system with the different detectors labeled [2].	62
5.5	Accordion geometry of the EMB in a plane transverse to the LHC beams [8].	63
5.6	Shapes of the LAr calorimeter current pulse in the detector and of the signal output after bipolar shaping.	64
5.7	Sketch of the EMB module where the different layers are visible	65

5.8	Block diagram of the current LAr readout electronics architecture	67
5.9	A sketch of one module of the tile calorimeter, showing alternating steel and scintillating material [2].	69
5.10	Schematic view of the MS in the y-z projection.....	71
5.11	Geometric layout of the ATLAS magnet system	72
5.12	The ATLAS Trigger and Data Acquisition (TDAQ) system in Run 2	74
6.1	Primary vertex identification in $Z \rightarrow \mu\mu$ in a collision event from 2017.	79
6.2	Illustration of the charged particle trajectory in a solenoidal field, along with the five track parameters ($d_0, z_0, \phi, \theta, q/p$)	80
6.3	Illustration of a merged pixel cluster due to very collimated charged particles.....	82
6.4	Illustration of the topo-clustering algorithm.....	86
6.5	Illustration of the path of an electron through the detector	90
6.6	Diagram of the superclustering algorithm for electrons and photons ..	92
6.7	Comparison of the dielectron invariant mass distribution of $Z \rightarrow ee$ events before after energy-scale corrections are applied to the candidate electrons	93
6.8	Discriminating variables used for electron and photon identification..	96
6.9	Transformed likelihood-based discriminant for the reconstruction of electron candidates	97
6.10	Efficiency of the electron identification working points as a function of E_T and η	98
6.11	Schematic representation of the photon identification discriminating variables.....	100
6.12	Illustration of the calorimeter isolation method.....	102
6.13	Efficiency of the different electron isolation working points.....	104
6.14	Efficiency of the different calo-only photon isolation working points ..	105
6.15	Comparison of the dimuon invariant mass distribution of $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events before and after muon-momentum calibration..	110
6.16	E_T^{miss} resolution for various soft term methods	114
7.1	Efficiency of the diphoton triggers.....	118

8.1	Transverse mass distribution of $W \rightarrow e\nu$ events and the dielectron mass distribution of $Z \rightarrow ee$ events.....	125
8.2	Timing distribution after Pass 0 of the offline timing calibration.....	128
8.3	Profile plot of cell energy versus time for passes 3 and 4.....	129
8.4	Profile plots of $\delta\eta$ and $\delta\phi$ for Pass 4 and Pass 5.....	130
8.5	Profile plots of f_1 and f_3 for Pass 5 and Pass 6.....	131
8.6	Timing distributions after application of all the timing corrections.....	132
8.7	Timing distributions of the $Z \rightarrow ee$ events after application of the timing calibration corrections.....	133
8.8	Timing resolution versus middle-layer cell energy.....	134
8.9	Distribution of the electron times for $Z \rightarrow ee$ events with satellite collisions observed at ± 5 ns.....	136
8.10	Illustration of photon pointing calculated using LAr calorimeter information.....	138
8.11	Resolution of the photon pointing variable as a function of $ z_{\text{origin}} $	140
8.12	Illustration of the calo-vertexing algorithm.....	141
8.13	Comparison of the 2D displacement variables for data and signal.....	142
8.14	Calo-vertex distributions for $Z \rightarrow ee$ events in data and simulation	143
8.15	Resolution of the V_T and V_z as a function of $\Delta\eta_{ee}$	144
8.16	Effect of a $\Delta\eta$ cut on the V_T and V_z distributions.....	144
8.17	V_T and V_z distributions for detector regions.....	145
9.1	Trigger efficiency for the HyyHSM and ZeeZSM signal samples for different photon ID working points.....	149
9.2	Photon isolation efficiency as a function of the photon time and pointing for the HyyHSM signal.....	150
9.3	Illustration of the timing quadrants.....	154
9.4	Distributions of event-level variables used to define the analysis regions.....	155
9.5	Illustration of the analysis regions in three-dimensional— E_T^{miss} , $m_{\gamma\gamma}$, and photon-time—hyperplane.....	156
9.6	Comparison of timing distributions for signal and data.....	158
9.7	Comparison of vertexing distributions for signal and data.....	159
9.8	Sensitive analysis variables— t_{avg} and ρ —for CR events in data and SR events in simulation.....	160

9.9 Sensitive analysis variables— t_{avg} and ρ —in the optimized analysis bins	161
10.1 Average photon timing distribution for the CR events split into real- and fake-enhanced templates	166
10.2 Distribution of the CR-to-SR $E_{\text{cell}}^{\text{maxE}}$ reweight values	167
10.3 Residual corrections to the lead and sublead photon timing	167
11.1 Photon purity fraction uncertainty variations.....	171
11.2 $E_{\text{cell}}^{\text{maxE}}$ reweight error uncertainty variations.....	172
11.3 Pileup profile uncertainty variations	173
11.4 Variations of the photon timing smearing.....	177
12.1 Significance thresholds chosen as convention for a claim, evidence, and discovery of a new physics process	181
12.2 Spurious signal and signal injection tests	186
12.3 Post-fit t_{avg} distributions for background-only fits to the VR-time data.....	189
12.4 Background-only fit pull distributions of the background systematic uncertainties in the three VRs	190
13.1 t_{avg} distributions for the post-fit background templates and the unblinded SR data.....	192
13.2 Pull distributions of the background systematics for a background-only fit to the SR data.....	193
13.3 Local p_0 -values for the HyyHSM and ZeeZSM signal models as a function of the $\tilde{\chi}_1^0$ mass and lifetime.....	195
13.4 95 % C.L. limit on $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ mass.....	196
13.5 95% C.L. limit on $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ lifetime	197
13.6 95% C.L. limits on $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ branching ratio to the SM Higgs boson.....	198
13.7 95% C.L. exclusion limits on the target signal hypothesis, for $\tilde{\chi}_1^0$ lifetime in ns as a function of $\tilde{\chi}_1^0$ mass in GeV	199
13.8 Excluded values of the $\tilde{\chi}_1^0$ mass as a function of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G})$ and the $\tilde{\chi}_1^0$ lifetime.....	200
A.1 Satellite collision events in the photon timing distributions in data	208

A.2	Prevalence of the satellite events for $E_T^{\text{miss}}, m_{\gamma\gamma}, \Delta\phi(\gamma_1, \gamma_2), p_T^{\gamma\gamma}$ distributions	209
A.3	Prevalence of the satellite events for ρ , photon ID, $E_{\text{cell}}^{\text{maxE}}(\gamma_1), E_{\text{cell}}^{\text{maxE}}(\gamma_2)$ distributions.....	210
A.4	Event display of the event 761048468, Run 359593	211
B.1	Comparison of t_{avg} distribution across the timing quadrants.....	212
B.2	Comparison of the various choices of the sensitive timing variable	214
B.3	Validation of the lifetime reweighting procedure	216
B.4	Resolutions of the various timing distributions	218

Chapter 1

Introduction

To begin at the beginning.

Arthur Conan Doyle
A Study in Scarlet

A search for new phenomena that are not described by the Standard Model (SM) of particle physics is described in this thesis. The search is performed with the ATLAS [2] experiment at the Large Hadron Collider (LHC) [6, 9]. The search presented uses the full Run 2 data set recorded by the ATLAS detector and corresponds to an integrated luminosity of 139 fb^{-1} of pp collisions at the center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$.

The SM of particle physics is a theory that describes three of the four fundamental forces, their interactions with the elementary particles, and the mutual interactions of these elementary particles. The SM is widely successful in explaining and predicting experimental observations over the past five decades. In July 2012, the discovery of the Higgs boson by the ATLAS and CMS experiments at the LHC [10, 11] demonstrated the existence of the last elementary particle predicted by the SM. Despite the exceptional success of the SM to describe the building blocks of matter, our current description of the subatomic world is incomplete.

Physicists have hypothesized the existence of several new particles, in theories beyond the Standard Model (BSM), to explain the SM and several of its unanswered questions. However, after a decade of meticulous research, the evidence of new particles remains out of sight. *What if these new particles are not where we expect to find them?*

The current approach for particle detection is to look for particles produced instantaneously and at the center of the detector. However, "long-lived" particles, i.e. particles that travel a non-zero distance from the center of the detector before being detected have largely remained an unexplored area in particle detection. Long-lived particles (LLPs) are well motivated in the SM and in several BSM theories. These LLPs could travel distances ranging from a couple of micrometers to about half a

meter before they decay. Therefore, the search for such particles is the next frontier in experimental particle physics.

Supersymmetry (SUSY) is a class of theories that provides an elegant framework to explain several shortcomings of the SM. Over decades of research, strong constraints have been set on several SUSY models. Although the possible phase space to realize SUSY has been highly constrained, the search for LLPs in the context of SUSY is gaining interest. A SUSY model which predicts LLPs provides a unique but challenging detection signature. Long-lived SUSY particles could travel, undetected, away from the center of the detector before decaying into particles that can be detected. An event with such a long-lived SUSY particle decay would be recognized as a "displaced vertex" signature. The detection of such displaced vertices requires an excellent understanding of the detector and its performance.

This thesis presents a search for an experimentally unique LLP signature: a displaced and delayed diphoton/dielectron vertex. The search exploits the capabilities of the ATLAS Liquid Argon (LAr) calorimeter to determine both the delay and displacement of this unique LLP signature. Results are presented in the context of the SUSY model considered in this thesis, and the results are also generalized in a model-independent interpretation.

The thesis is organized as follows: Chapter 2 provides an overview of the Standard Model and some shortcomings of the theory. Chapter 3 provides a theoretical overview of SUSY, the SUSY model with the LLP signature studied in this thesis, and motivation for LLPs and the unique LLP signature explored in this thesis. Chapter 4 provides a review of accelerator concepts, an overview of the LHC, and the operating conditions of the ATLAS detector in Run 2. Chapter 5 provides a description of the ATLAS experiment, the sub-systems of the ATLAS experiment, especially the calorimeter, and the trigger and data acquisition system. Chapter 6 provides an in-depth description of the reconstruction of physics objects with an emphasis on the reconstruction techniques of electromagnetic objects. Chapter 7 describes the choice of the trigger, event selections, the Monte Carlo simulation process, and the grid of the simulated signal samples. Chapter 8 describes in detail the calibration of the timing measurements obtained from the LAr calorimeter and a novel vertex localization algorithm developed for the search. Chapter 9 describes the event selections developed for the search, the analysis regions developed to

estimate the background and search for the LLP signal, and the sensitive variables developed to search for delayed and displaced particles. Chapter 10 describes in detail the background estimation strategy developed to derive the background model expected in the region sensitive to the LLP signal. Chapter 11 describes the sources of uncertainties applied to the background and the signal models. Chapter 12 provides a review of the statistical analysis methods and the fit framework developed for the search. Chapter 13 describes the results of the search in the context of the SUSY model under study, as well as a model-independent interpretation. Chapter 14 concludes with an outlook on the context of the experimental landscape at the LHC and the future efforts to build up on the work presented in this thesis.

Chapter 2

The Standard Model and Beyond

Three quarks for Muster Mark!

James Joyce
Finnegan's Wake

2.1 The Standard Model of Particle Physics...

The Standard Model (SM) describes the elementary particles which constitute matter, their mutual interactions, and their interactions with the fundamental forces through the exchange of force-carrier particles. The particle content and the basic properties of the SM are discussed in section 2.1.1. The SM describes three of the four fundamental forces: the strong force, the weak force, and electromagnetism. Gravitational interactions are not described by the SM, which is one of the significant limitations of the model. Some of the most important shortcomings of the SM are discussed in Section 2.2.

2.1.1 Standard Model

The Standard Model is a field theory description of the fundamental particles and their interactions through the strong force, the weak force, and electromagnetism. According to this model, matter is composed of fermions, called *leptons* and *quarks*, both of which have a spin of $1/2$. The fermions are further categorized into three different generations. The first generation includes the electron (e), which has one unit of negative electric charge, and the electrically neutral electron neutrino (ν_e), both of which participate in the weak interaction. Since the electron is electrically charged, it can also interact through electromagnetic force. Quarks, on the other hand, have fractional electric charges and participate in all three of the fundamental forces. The first generation of quarks includes the up quark (u), which has an electric charge of $+2/3$, and the down quark (d), which has a negative electric charge of $-1/3$.

The two additional generations of leptons and quarks contain almost identical copies of the particles, differing only in their masses. The muon (μ) and tau (τ) are two negatively charged leptons that complement the electron. Similarly, the muon neutrino (ν_μ) and tau neutrino (ν_τ) complement the electron neutrino. The up quark is complemented by two heavier quarks, the charm (c) and the top (t), while the bottom quark is complemented by the strange (s) and the heavier bottom (b) quarks. A minimal particle content of the SM is shown in Fig 2.1.

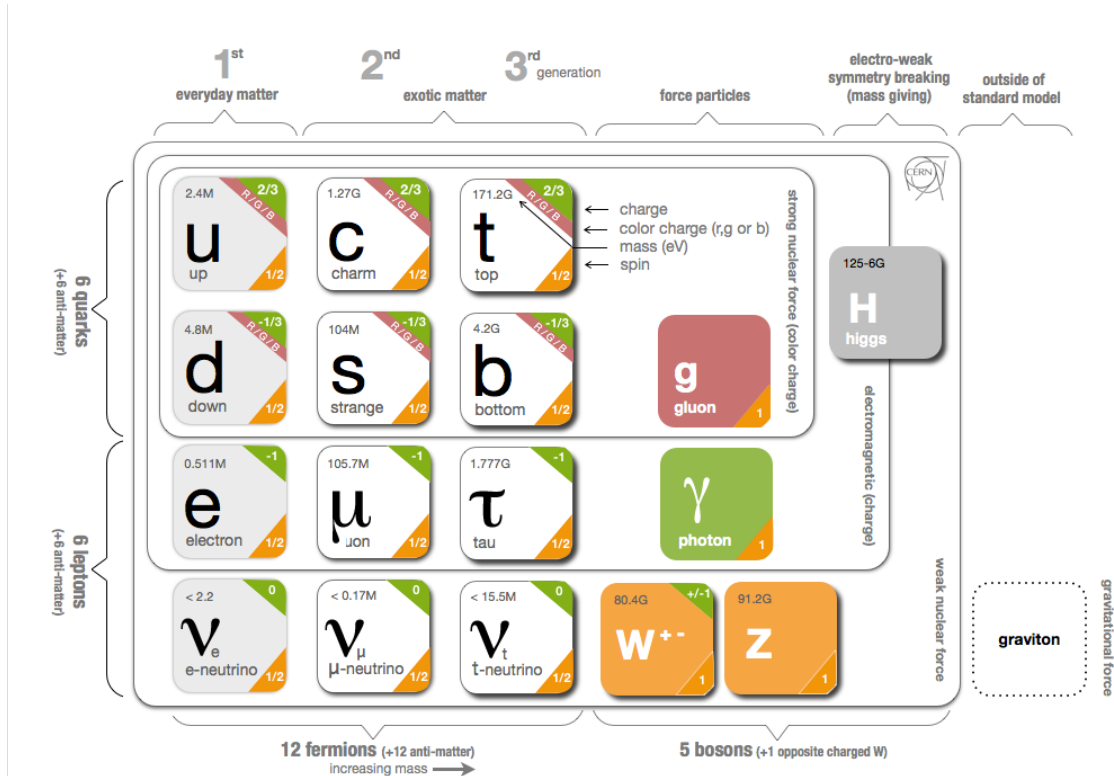


Figure 2.1: Particle content of the Standard Model [5].

The fundamental forces are mediated through the exchange of spin-1 gauge bosons. The electromagnetic force is mediated by the photon, γ , and the strong force is mediated by the gluon. Both the photon and the gluon are electrically neutral and massless. The massive $W^\pm$ and Z^0 bosons mediate the weak force. The W boson carries one unit of electric charge, whereas the Z boson is electrically neutral. The final component of the SM is the recently discovered spin-0 and electrically neutral

Higgs boson [10, 11], H , which is a remnant of the electroweak symmetry breaking mechanism [12–16] that generates the masses of the SM particles.

The SM is a Lorentz invariant, quantum field theory (QFT), described by the local gauge symmetry group [17]

$$SU(3)_C \times SU(2)_L \times U(1)_Y \quad (2.1)$$

Quantum Chromodynamics (QCD) is the theory of strong interaction, described by the $SU(3)_C$ group. This group is associated with a property known as "color" which can have three values, namely *red*, *green*, and *blue*. The eight gluon states act as generators of this group, and are responsible for mediating interactions between quarks and other gluons.

The electroweak theory is a unified theory that is described by the product of $SU(2)_L$ and $U(1)_Y$. The $SU(2)_L$ group represents weak isospin symmetry, I , which acts only on the left-handed components of fermions. On the other hand, the $U(1)_Y$ group represents weak hypercharge symmetry, denoted by Y . The three generators of $SU(2)_L$ correspond to three vector gauge bosons, W^1 , W^2 , and W^3 , while the generator of $U(1)_Y$ corresponds to the vector gauge field, B . The weak and electromagnetic gauge bosons are identified with the W^1 , W^2 , and W^3 gauge bosons as follows:

$$W^\pm = \frac{1}{\sqrt{2}}(W^1 \mp iW^2) \quad (2.2)$$

The neutral field B and W^3 mix to form the states

$$Z = W^3 \cos \theta_W - B \sin \theta_W \quad (2.3)$$

$$A = W^3 \sin \theta_W + B \cos \theta_W \quad (2.4)$$

where θ_W is the weak mixing angle which has to be determined experimentally. The two physical states Z and A are the mass eigenstates associated with the massive Z boson and the massless photon, γ , respectively.

Explicit mass terms for the fermions and gauge bosons in the SM are not gauge invariant and therefore are forbidden. Consequently, the electroweak $SU(2)_L \times$

$U(1)_Y$ symmetry is broken. The Higgs mechanism is responsible for the generation of the masses of the SM particles via the spontaneous breaking of the electroweak symmetry. In a nutshell, the theory postulates that a complex scalar doublet field, ϕ , exists which has non-zero vacuum expectation value (VEV), ϕ_0

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.5)$$

where v is a constant measured to be $v = 246$ GeV.

Upon acquiring a non-zero VEV, the $SU(2)_L \times U(1)_Y$ symmetry is spontaneously broken to a $U(1)_Q$ symmetry. Of the four degrees of freedom of the ϕ field, three degrees of freedom are absorbed by the $W^\pm$ and Z bosons to create their longitudinal polarizations and become massive, with masses proportional to v . As a consequence of $U(1)_Q$ gauge invariance, the photon remains massless. The fourth degree of freedom is identified as a new massive scalar, the Higgs boson, H , with its mass determined experimentally. Finally, fermion masses, m_f , are generated by so-called Yukawa terms, which also introduce couplings to the Higgs boson proportional to m_f/v .

2.2 ... and Beyond

The SM has undergone stringent tests over the last 50 years, with the discovery of the Higgs boson in July 2012 [10, 11] completing the final piece of the SM particle-puzzle. Despite the monumental success of the SM to explain the fundamental particles and their interactions, it is far from being a complete theory of Nature. The following subsections briefly summarize some major limitations of the SM.

2.2.1 Naturalness of the Higgs Boson Mass

The mass of the Higgs boson has been found to be 125.25 ± 0.17 GeV [18], which is in the same energy scale ($\mathcal{O}(10^2)$ GeV) of the electroweak physics. The physical mass of the Higgs boson is a combination of the bare mass ($m_{H,\text{bare}}$) from the SM

Lagrangian and additional contributions from quantum fluctuations:

$$m_H^2 = m_{H,\text{bare}}^2 + \delta m_H^2 \quad (2.6)$$

where, m_H is the Higgs boson mass and δm_H^2 are the quantum corrections to the Higgs boson mass. The largest contribution to the Higgs boson mass comes from the one-loop contributions from the Higgs-top quark coupling. The corrective contribution from the top quark loop can be expressed as:

$$\delta m_H^2 = \frac{y_t^2}{16\pi^2} \Lambda_c^2 \quad (2.7)$$

where, y_t is the top quark Yukawa coupling and Λ_c is the cutoff value of momentum in the top quark loop. If the SM is a valid theory up to a very high scale, e.g., $\Lambda_c \sim 10^{18}$ GeV, then the bare mass, $m_{H,\text{bare}}$, has to be a very large and an extraordinarily fine-tuned number to cancel the very large ($\mathcal{O}(10^{36})$ GeV²) contribution from the one-loop top quark correction, thereby reproducing the observed Higgs boson mass around 125 GeV. This unnatural fine-tuning of the bare Higgs boson mass in the SM is called the *naturalness* problem. It is known that the fermions and bosons contribute with opposite signs to the Higgs mass calculation. These two contributions might cancel if each SM boson had a fermionic partner of the same mass, and vice versa. Therefore, assuming a boson-fermion symmetry could provide a possible solution to the naturalness problem (cf. Supersymmetry in Chapter 3).

2.2.2 Gravity

At the energy scales probed by the LHC and previous collider experiments, the effect of gravity can be safely ignored. The energy scale at which the gravitational force cannot be neglected is called the Planck scale $\mathcal{O}(10^{19})$ GeV [19]. Although several theories of quantum gravity have been formulated, the absence of clear experimental evidence makes it difficult to establish their concrete connection with the SM.

2.2.3 Dark Matter and Dark Energy

The SM fails to explain two major astrophysical observations: Dark Matter and Dark Energy. The existence of non-luminous and non-absorbing matter, called Dark Matter, is considered responsible for the discrepancies between the predicted and observed gravitational effects on the ordinary, luminous matter [20–23]. The SM does not provide a candidate for Dark Matter, therefore Beyond Standard Model (BSM) theories attempt to provide a stable, non-interacting, or only weakly-interacting particle that could constitute the bulk of the Dark Matter. The SM also provides no mechanism for Dark Energy which is hypothesized to explain the observed acceleration of the expansion of the Universe [24, 25].

2.2.4 Matter-Antimatter Asymmetry

The Big Bang should have created equal amounts of matter and antimatter. However, if we extrapolate the conditions of the early Universe a billionth of a second after the Big Bang there was a slight majority of matter particles over the antimatter particles. For every billion particle-antiparticle pairs, there was one extra particle [26]. The SM does not provide an explanation for the observed matter-antimatter asymmetry. A source of asymmetry comes from the CP¹ violating complex phase in the quark mixing matrix of weak interactions. However, the electroweak CP violating phase does not account for the observed asymmetry [27].

¹CP refers to the combined charge-conjugation (C) and parity (P) symmetries. Charge conjugation flips the sign of the particle, i.e., interchanging a particle with its anti-particle, and vice versa. Parity (P) flips the momentum of the particle while preserving its spin. Therefore, CP flips a particle to its anti-particle and also flips its spatial coordinates.

Chapter 3

Supersymmetry

Thou hast seen nothing yet.

Miguel de Cervantes Saavedra

Don Quixote

3.1 Introduction

Supersymmetry (SUSY)[28–36] is a generalization of the space-time symmetries of the quantum field theory that transforms fermions into bosons and vice versa [37]. SUSY is a family of theoretical models motivated to provide solutions to some of the issues that remain unanswered by the SM. The operator, Q , encodes the transformation of the fermionic states to bosonic states and vice versa.

$$Q |\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q |\text{Fermion}\rangle = |\text{Boson}\rangle \quad (3.1)$$

The operator, Q and its hermetian conjugate $Q^\dagger$ are generators of the supersymmetry transformation [38, 39]. In the most general form, there can be more than one supersymmetric transformation, which translates to more than one distinct copy of the generator pairs, Q and $Q^\dagger$. In this thesis, we consider the case where the number of generators, $N = 1$. It can be shown that the application of the supersymmetry operators on a particular state produces a state with the same mass and identical quantum numbers. It can be further shown that the two states which are transformed by the operator Q will differ by spin-1/2 [40].

An important consequence of the above result is that for each bosonic (fermionic) degree of freedom in the SM, there exists a fermionic (bosonic) degree of freedom identical in all aspects except the spin. The SUSY counterparts of SM particles are called *superpartners*. An SM particle and a SUSY *superpartner* are arranged in *supermultiplets*, which are irreducible representations of the SUSY algebra. Therefore, we can form supermultiplets by considering the spin of the SM particles and pairing them with the corresponding sparticle. For $N = 1$ SUSY extension, the simplest case

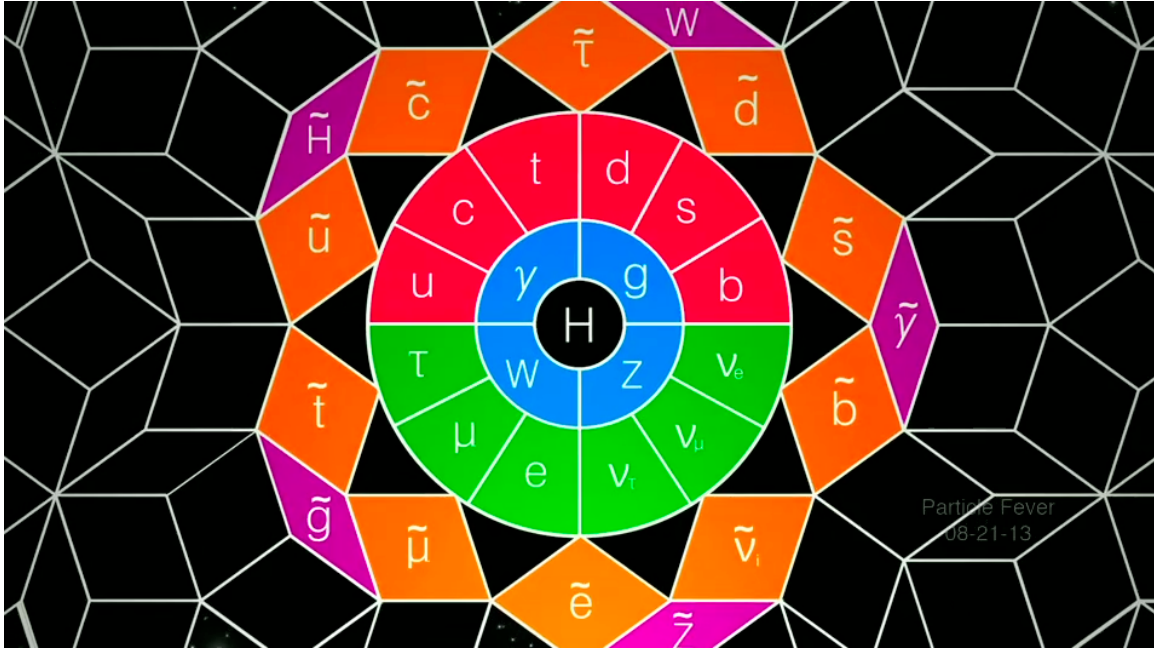


Figure 3.1: Artistic representation of the SM and SUSY particles. The SUSY particles, called *sparticles* are denoted by a tilde superscript ($\sim$) [41].

would be to consider scalar particles (spin-0) as superpartners of the SM fermions (spin-1/2). The fermions and their superpartners are together arranged in a *chiral* supermultiplet. Similarly, an SM gauge boson (spin-1) will have a fermionic (spin-1/2) superpartner. The gauge bosons and their superpartners are together arranged in a *vector/gauge* multiplet. For the case of scalar bosons such as the Higgs boson, the appropriate superpartner would be a spin-1/2 particle. Finally, if the theory includes gravity, the graviton (spin-2) will be assigned a spin-3/2 superpartner. The naming convention for superpartners is as follows: the names of the spin-0 superpartners of the fermions are constructed by prepending an "s", for a scalar. For e.g., one would name the superpartners of the fermions as *sfermions*. The names of the spin-1/2 superpartners of the gauge bosons are constructed by appending an "ino". For e.g., one would name the superpartners of the gauge bosons as *gauginos*.

3.2 Minimal Supersymmetric Standard Model

In the minimal supersymmetric extension of the SM (MSSM), each of the known fundamental particles is either in a chiral or a vector supermultiplet. The SM gauge

bosons, and their superpartners the gauginos, are naturally arranged in vector or gauge supermultiplets. Therefore, for the SM gluon, the W and B bosons, the corresponding superpartners are the gluino, wino, and bino respectively. The left-handed SM fermions are arranged in an $SU(2)_L$ doublet chiral supermultiplet with their superpartners. Similarly, the right-handed SM fermions are arranged in an $SU(2)_R$ singlet chiral supermultiplet with their superpartners.

Although it may seem obvious that the spin-0 Higgs boson must be arranged in one chiral supermultiplet, just one chiral supermultiplet is not enough. The Higgs supermultiplets consist of two complex Higgs doublets, their *Higgsino* fermionic superpartners, and the corresponding antiparticles. This enlarged Higgs sector is the minimal structure needed to guarantee the cancellation of gauge anomalies [42] generated by the Higgsino superpartners. Moreover, without a second Higgs doublet, one cannot generate masses for both the "up-type" and the "down-type" quarks.

The particle content of the MSSM and their properties under the SM groups are shown in Table 3.1.

The introduction of supersymmetric partners of the SM particles provides an elegant solution to the hierarchy problem. The addition of heavy charged scalar particles in supersymmetric theories has the potential to cancel the fermionic contributions to loop corrections of the Higgs mass since the fermions and scalars contribute with the opposite sign.

An additional attractive feature of MSSM is the prediction of the unification of the gauge couplings. Extending the SM to the MSSM and using the MSSM particle content, the three SM gauge couplings unify at a point scale $M_U \simeq 3 \times 10^{16}$ GeV [43].

In the SM, baryon (B) and lepton (L) numbers are accidentally conserved. However, in MSSM there are renormalizable terms that violate baryon and/or lepton numbers. $B - L$ number violation introduces the problem of proton decay, which has not been observed experimentally [18]. To conserve the stability of the proton, an additional symmetry is introduced in many SUSY models called the R parity [44, 45]. For a particle with spin s , baryon and lepton numbers B , and L , respectively, the R parity is defined as

$$R \equiv (-1)^{3(B-L)+2s} \quad (3.2)$$

Chiral supermultiplets			
Content	spin-1/2	spin-0	$(\text{SU}(3)_C, \text{SU}(2)_L, \text{U}(1)_Y)$
lepton–slepton	$(\nu \ e_L)$	$(\tilde{\nu} \ \tilde{e}_L)$	$(1, 2, -\frac{1}{2})$
	$e_R^\dagger$	$\tilde{e}_R^*$	$(1, 1, 1)$
quark–squark	$(u_L \ d_L)$	$(\tilde{u}_L \ \tilde{d}_L)$	$(3, 2, \frac{1}{6})$
	$u_R^\dagger$	$\tilde{u}_R^*$	$(\bar{3}, 1, -\frac{2}{3})$
	$d_R^\dagger$	$\tilde{d}_R^*$	$(\bar{3}, 1, \frac{1}{3})$
Higgs–Higgsino	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(H_u^+ \ H_u^0)$	$(1, 2, \frac{1}{2})$
	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(H_d^0 \ H_d^-)$	$(1, 2, -\frac{1}{2})$
Gauge supermultiplets			
Content	spin-1	spin-1/2	$(\text{SU}(3)_C, \text{SU}(2)_L, \text{U}(1)_Y)$
gluon–gluino	g	$\tilde{g}$	$(8, 1, 0)$
W boson–winos	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	$(1, 3, 0)$
B boson–bino	B^0	$\tilde{B}^0$	$(1, 1, 0)$

Table 3.1: The chiral and gauge supermultiplets in the Minimal Supersymmetric Standard Model (MSSM). Only the first generation of quarks and leptons are shown, with identical properties understood for the second and third generations.

Therefore, SM particles have even ($R = 1$) parity and sparticles have odd ($R = -1$) parity. The conservation of R-parity has a critical impact on supersymmetric phenomenology. For e.g., any initial state in a scattering experiment will be a state with R-even parity. Since sparticles have odd parity they have to be produced in pairs. Moreover, R-parity invariance also implies that the lightest supersymmetric particle (LSP) cannot decay into an SM particle; therefore the LSP must be stable and must eventually be produced at the end of a decay chain initiated by the decay of a heavy unstable sparticle. In addition, consistency with the cosmological constraints requires the stable LSP to be electrically and color neutral [46]. Consequently, the LSP in an R-parity conserving (RPC) theory is weakly interacting with ordinary matter, and the stability of the LSP in RPC SUSY makes it a promising candidate for Dark Matter [47, 48].

It is worth noting that one can construct models which are R-parity violating (RPV). The supersymmetric phenomenology of the RPV models exhibits features that are different from that of the MSSM. The LSP is no longer stable, which implies not all sparticle decay chains must yield missing energy events at particle colliders. RPV models exhibit rich and challenging topologies that are being searched at the ATLAS experiment.

3.3 SUSY is a broken symmetry?

An important observation from the previous sections is that, even in the most minimal models of SUSY, several new superpartners (sparticles) with masses equal to their SM counterparts are predicted. However, since no supersymmetric particles have been discovered yet, one has to assume that supersymmetry is *not* an exact symmetry, but a broken symmetry. It can be shown [49, 50] that by adding "soft" breaking terms ($\mathcal{L}_{\text{soft}}$) to the SUSY Lagrangian ($\mathcal{L}_{\text{SUSY}}$), the ultraviolet properties of the theory can be preserved. With the soft-SUSY breaking, and the assumption that the sparticle masses should be on the order of a few TeV, the origin and the stability of the gauge hierarchy can be preserved.

Symmetry breaking in SUSY is analogous to the SM electroweak symmetry breaking. Since there are two Higgs supermultiplets in MSSM, each supermultiplet obtains a non-zero vacuum expectation value (VEV). The ratio of the two VEVs, $\tan\beta$, and the sign of the Higgsino mass parameter, $\text{sgn}(\mu)$ are some important SUSY-breaking parameters.

The Higgs scalar fields in the MSSM consist of eight real, scalar degrees of freedom. After electroweak symmetry breaking, three of the eight degrees of freedom are "eaten" up by the gauge bosons to provide their longitudinal modes and mass. The remaining five degrees of freedom correspond to five mass eigenstates — h^0 , H^0 , A^0 , H^- , and H^+ . The masses of H^0 , A^0 , and $H^\pm$ can be arbitrarily large, however, the mass of h^0 is bounded above [51, 52]

$$m(h^0) < m_Z |\cos(2\beta)| \quad (3.3)$$

here, m_Z is the Z-boson mass, and β is the ratio of the two VEVs. Clearly, the above bound is violated with the observation of a 125 GeV Higgs boson [18]. Thus, either

large tree-level corrections or large radiative corrections are needed to increase this upper bound. The former requires new field content beyond the MSSM while the latter can occur in MSSM.

With the electroweak symmetry breaking, the higgsinos and the electroweak gauginos mix with each other. The neutral higgsinos ($\tilde{H}_u^0, \tilde{H}_d^0$) and the neutral gauginos ($\tilde{W}^0, \tilde{B}$) combine to form four mass eigenstates called *neutralinos*. The charged higgsinos ($\tilde{H}_u^\pm, \tilde{H}_d^\pm$) and winos ($\tilde{W}^\pm$) mix to form two charged, mass eigenstates called *charginos*. The neutralino mass eigenstates are denoted as $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$. Similarly, the chargino mass eigenstates are denoted as $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$. By convention, the neutralinos and charginos are labeled in ascending order, such that $m(\tilde{\chi}_1^0) < m(\tilde{\chi}_2^0) < m(\tilde{\chi}_3^0) < m(\tilde{\chi}_4^0)$, and $m(\tilde{\chi}_1^\pm) < m(\tilde{\chi}_2^\pm)$.

The gluino is a color octet fermion, so it cannot mix with any other particle in the MSSM, even if R-parity is violated. Analogous to the lepton and quark mixing in the SM, mixing can occur in the up- and down-type squarks, sleptons, and sneutrinos. The mass eigenstates of the squarks and sleptons are obtained by diagonalizing three 6×6 squared-mass matrices for up-type squarks ($\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R$), down-type squarks ($\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$), and charged sleptons ($\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$), and one 3×3 matrix for sneutrinos ($\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$). The mixing angles for the first two generations are small, therefore, the first and second generation squarks and sleptons are their own mass eigenstates. The mixing in the third generation is substantial, compared to the first two generations, because of the relatively large Yukawa couplings. The particle content of the MSSM after the electroweak symmetry breaking is shown in Table 3.2.

For the theory to incorporate gravity, SUSY should be promoted to a local symmetry. The resulting local supersymmetric theory is called *supergravity* [53–59]. In supergravity, the spin-2 graviton has a spin-3/2 superpartner, called the *gravitino*. As long as supersymmetry is unbroken, the graviton and gravitino are both massless. Once SUSY is spontaneously broken, the gravitino acquires mass by absorbing the goldstino—an analog to the Nambu-Goldstone boson of the Higgs mechanism of the electroweak symmetry breaking. The mechanism of spontaneous SUSY-breaking is called the "super-Higgs" mechanism and is analogous to the SM Higgs mechanism by which the $W^\pm$ and Z^0 gauge bosons acquire mass. In the

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0 \ H_d^0 \ H_u^+ \ H_d^-$	$h^0 \ H^0 \ A^0 \ H^\pm$
neutralinos	1/2	-1	$\tilde{B} \ \tilde{W}^0 \ \tilde{H}_u^0 \ \tilde{H}_d^0$	$\tilde{\chi}_1^0 \ \tilde{\chi}_2^0 \ \tilde{\chi}_3^0 \ \tilde{\chi}_4^0$
charginos	1/2	-1	$\tilde{W}^\pm \ \tilde{H}_u^\pm \ \tilde{H}_d^\pm$	$\tilde{\chi}_1^\pm \ \tilde{\chi}_2^\pm$
gluino	1/2	-1	$\tilde{g}$	(same)
squarks	0	-1	$\tilde{u}_L \ \tilde{u}_R \ \tilde{d}_L \ \tilde{d}_R$	(same)
			$\tilde{s}_L \ \tilde{s}_R \ \tilde{c}_L \ \tilde{c}_R$	(same)
			$\tilde{t}_L \ \tilde{t}_R \ \tilde{b}_L \ \tilde{b}_R$	$\tilde{t}_1 \ \tilde{t}_2 \ \tilde{b}_1 \ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L \ \tilde{e}_R \ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L \ \tilde{\mu}_R \ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L \ \tilde{\tau}_R \ \tilde{\nu}_\tau$	$\tilde{\tau}_1 \ \tilde{\tau}_2 \ \tilde{\nu}_\tau$
gravitino	3/2	-1	$\tilde{G}$	(same)

Table 3.2: Particle content of the MSSM.

super-Higgs mechanism, the gravitino mass is given by

$$m(\tilde{G}) = \frac{\langle F \rangle}{\sqrt{3}m_P} \quad (3.4)$$

where, $\langle F \rangle$ is the non-zero VEV, and m_P is the Planck mass.

Several mechanisms have been proposed for spontaneously-broken weak-scale supersymmetry breaking. A common feature among these models is that SUSY breaking occurs in a *hidden* sector. The hidden sector comprises fields that do not have gauge or superpotential couplings with the *visible* sector containing the MSSM. The effects of the hidden sector supersymmetry breaking are then transmitted to the visible sector via *messenger fields*. Several models have been developed that primarily focus on the mechanism of symmetry-breaking via messenger fields. In gauge-mediated supersymmetry breaking (GMSB), gauge forces transmit the supersymmetry breaking to the visible sector. In gravity-mediated supersymmetry breaking, the gravitational force transmits the supersymmetry breaking to the visible sector. The scenario investigated in this thesis is a part of the GMSB family

of models and is therefore discussed in more detail below.

3.4 Gauge Mediated Supersymmetry Breaking

In Gauge Mediated Supersymmetry Breaking (GMSB) [60–65], the gauge interactions are responsible for the soft-breaking of supersymmetry in the MSSM. GMSB models involve a hidden sector where SUSY is broken, a messenger sector, and a visible sector that contains the quarks, leptons, and the two Higgs doublets, together with their supersymmetric partners. The messenger particles are new chiral supermultiplets that couple to the hidden sector and also couple indirectly to the visible sector via the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge interactions. The messenger particles acquire mass in the hidden sector through Yukawa couplings with the goldstino superfield, whose non-zero VEV generates SUSY breaking. The masses of the messenger particles are characterized by an overall mass scale M_{mess} and mass splitting $\sqrt{F}$. The mass splitting arises because of the gauge interactions between the visible and messenger fields. The SM gauge boson and fermion masses are protected by gauge invariance. However, the sfermions and gauginos can acquire masses at one-loop and at two-loop level, respectively [66].

A theoretically appealing aspect of the GMSB models is the degeneracy of the squark and slepton masses needed for the suppression of flavor-changing neutral currents. Another distinctive phenomenological prediction of GMSB models may be the fact that the gravitino is the *lightest supersymmetric particle (LSP)*, with gravitino masses typically on the order of a few KeV. Assuming R-parity conservation, all sparticles will eventually decay to the stable gravitino. GMSB models can be generalized in a number of different ways including arbitrary messenger masses and messenger supermultiplets that do not form complete multiplets in an $SU(5)$ unified theory [40]. However, the gravitino as the LSP and the degeneracy of squarks and sleptons remain general features of such models.

3.5 Long-lived particles

The search for long-lived particles (LLPs) is intimately tied to the detection tools. Collider experiments are designed to look for decays of new particles which

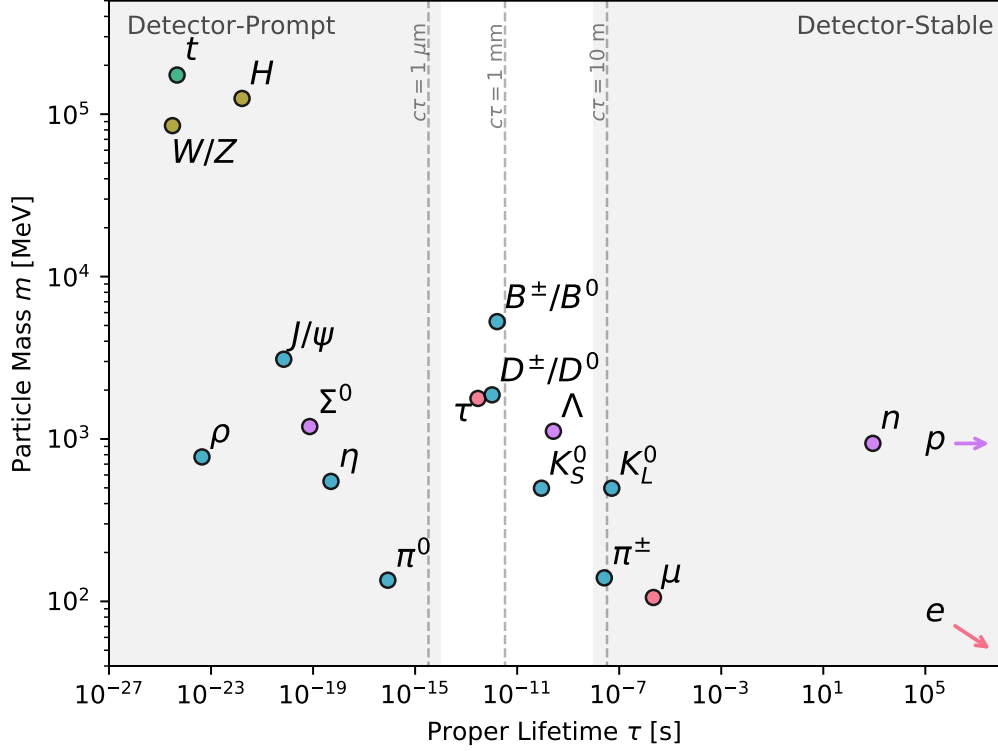


Figure 3.2: The SM contains many metastable particles. A selection of the SM particle spectrum is shown as a function of mass and proper lifetime. Shaded regions roughly represent the detector-prompt and detector-stable regions of lifetime space, for a particle moving at close to the speed of light [67].

occur quickly enough that they appear prompt. This expectation has impacted the design of detectors, as well as particle reconstruction and identification techniques and algorithms. However, there are several mechanisms by which particles may be *metastable* or even *stable*, with decay lengths that are significantly larger than the spatial resolution of the detector, or larger than the scale of the entire detector [67]. The impact of such mechanisms can be seen in the wide range of lifetimes of particles of the SM, shown in Figure 3.2. LLPs are an important part of the phenomenology of the BSM theories such as the GMSB mechanism for SUSY. The phenomenology of the GMSB models gives rise to a wide range of LLPs, with lifetimes ranging from $\mathcal{O}(1 - 100)$ ns.

The proper lifetime of a particle (τ) is given by

$$\tau^{-1} = \Gamma = \frac{1}{2m_\chi} \int d\Pi_f |\mathcal{M}(m_\chi \rightarrow \{p_f\})|^2 \quad (3.5)$$

Here, m_χ is the mass of the particle, $\mathcal{M}$ is the matrix element for the particle's decay into the decay product $\{p_f\}$, and $d\Pi_f$ is the Lorentz-invariant phase space for the decay. The formula assumes $\hbar = c = 1$. For a particle to be long-lived, there must be a small matrix element or a limited decay phase space. Several mechanisms lead to a small matrix element—mass-degenerate spectra, small couplings, or hierarchies of energy scale. One can draw examples from the SM particles to understand how each of the aforementioned mechanisms can lead to a small matrix element.

If the masses of the parent and the children particles are nearly degenerate, then the decay rate can be suppressed. E.g., consider the decay of a free neutron which occurs via the weak interaction. Since the decay of the neutron occurs via the exchange of a massive virtual W boson, the decay rate is suppressed. In addition, the mass difference between the proton and the neutron is small due to isospin symmetry. Therefore, the decay rate of the free neutron is further suppressed.

An excellent example of small couplings suppressing the decay rate is the decay of the b quark. The b quark can decay into an up or a charm quark via the weak interaction. The CKM elements V_{cb} and V_{ub} specify the decay rates. Since the off-diagonal CKM elements such as V_{cb} and V_{ub} are very small, the decay rates of the b quark to up and charm quarks are highly suppressed. Thus, the b quark is sufficiently long-lived such that it travels $\mathcal{O}(\text{cm})$ from the primary interaction point before decaying. This distinctive property of the b quark decay is used in collider experiments to perform *b-tagging* which identifies the b quark from other light quarks.

Although the above mechanisms were discussed in the context of SM particles, the same phenomenological reasons can be applied to BSM particles. Several SUSY models posit naturally long-lived particles because of the hierarchy of the energy scale, weak couplings, or mass degeneracy. Therefore, it is theoretically well-motivated to consider the possibility of long-lived particle signatures.

3.6 Displaced and delayed electromagnetic objects

In several GMSB models, the lightest neutralino ($\tilde{\chi}_1^0$) is the *next-to-lightest-supersymmetric particle* (NLSP). The NLSP mass eigenstate is a mixture of the Bino, Wino, and Higgsino gauge eigenstates. If the NLSP has a significant Higgsino or Wino component, then it can have $\mathcal{O}(1)$ branching ratio to $H + \tilde{G}$ and $Z + \tilde{G}$ [68]. The possibility of such signatures was first raised in [69–73]. Subsequent decays of the Higgs and Z boson can give rise to signatures with charged particles or photons and energy carried away by the LSP. In particular, the $Z \rightarrow ee$, $H \rightarrow \gamma\gamma$ plus the energy carried away by the LSP are possible signatures that are explored in this thesis.

The NLSP lifetime is determined by the fundamental SUSY breaking scale, $\sqrt{F_0}$. For $\sqrt{F_0} \simeq 10^2$ TeV, the NLSP decays promptly, while for $\sqrt{F_0} \sim 10^2\text{--}10^3$ TeV, the NLSP is sufficiently long-lived such that it decays away from the primary collision vertex, but inside the detector. Thus, the non-zero flight path of the NLSP will produce a *displaced* decay vertex.

Since the NLSP is massive and long-lived, if produced in the primary collision the NLSP will travel undetected through the detector before decaying into an SM particle plus the gravitino. The subsequent decay of the SM particle will be prompt compared to the flight time of the NLSP. The non-zero flight time of the NLSP results in the SM decay products being detected with a delay compared to those produced in the primary collision vertex. Therefore, a characteristic of long-lived particle decay is the detection of particles that are *delayed*.

A conceptual representation of a displaced vertex signature is shown in Figure 3.3. In this illustration, a slice of the high-energy collider detector is represented. The black dot represents the primary collision vertex where the NLSP may be produced. The NLSP travels through the inner detector; the flight path of the NLSP is shown with a dashed red line. The NLSP then decays into a pair of electron/photon objects whose showers are represented as two purple cones. These cones represent the total energy deposited in the electromagnetic calorimeter. If one were to extrapolate the common point of origin for the two electrons/photons, then the common point of origin would not correspond to the primary collision vertex. Thus, the two electromagnetic jets arise from a secondary, displaced vertex.

This thesis focuses on a GMSB model with the $\tilde{\chi}^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$ forming an almost

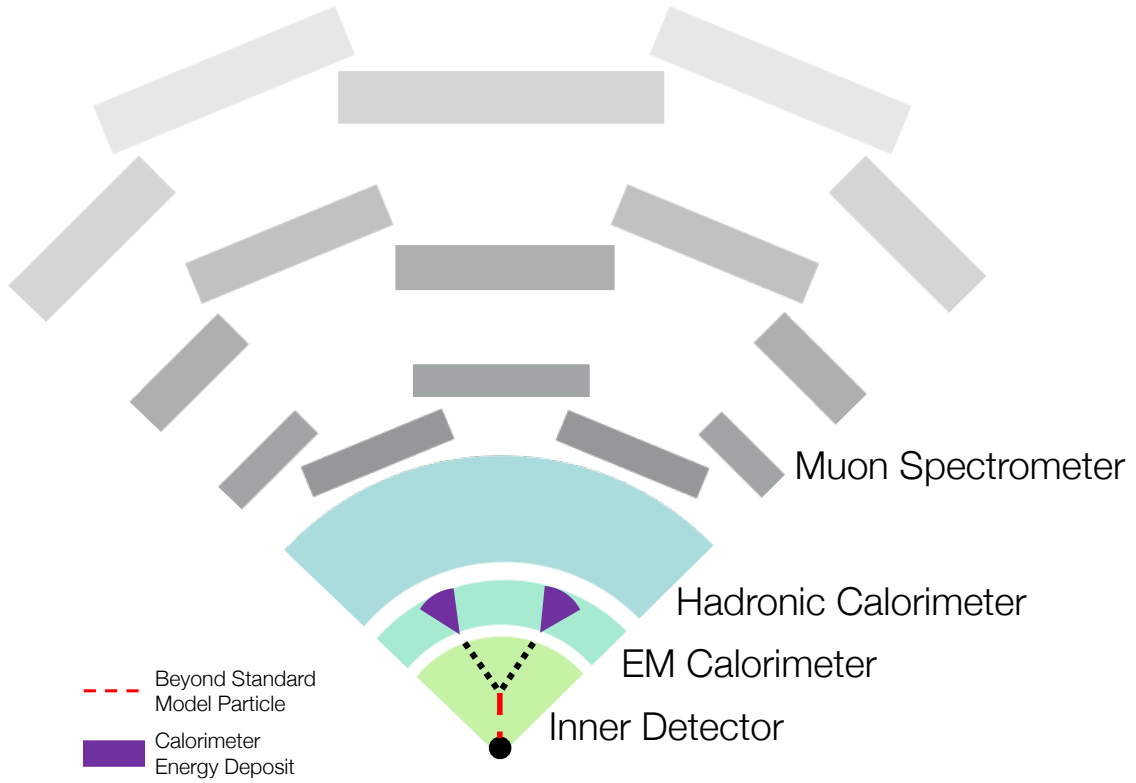


Figure 3.3: Conceptual representation of the signature of a displaced vertex produced from the decay of an NLSP which travels a non-zero distance from the primary collision vertex before decaying into $H/Z + \tilde{G}$. Here, the $H \rightarrow \gamma\gamma/Z \rightarrow ee$ decay mode is shown where the photons/electrons are reconstructed as energy deposits in the electromagnetic calorimeter. Not shown in this illustration is the $\tilde{G}$ which escapes detection.

degenerate triplet of SUSY partners of the SM electroweak bosons. The model signature consists of the direct pair production, where each sparticle decays to the NLSP and an SM particle, followed by the subsequent NLSP decay via Higgs/Z boson plus gravitino. One of the pair-produced $\tilde{\chi}_1^0$ is forced to decay to either a $H \rightarrow \gamma\gamma$ or $Z \rightarrow ee$ final state with a 100% decay rate. The other $\tilde{\chi}_1^0$ decays to a Higgs or Z boson which subsequently decays to their SM-allowed decay products. Since the NLSP is long-lived, the NLSP decay vertex is thus displaced from the primary collision vertex. Because of the non-zero flight time of the NLSP, the measured arrival time of the photons/electrons to the electromagnetic calorimeter is *delayed* compared to those produced in the primary collision.

Feynman diagrams for the signal process are shown in Figure 3.4. The signal signature consists of the pair-production of $\tilde{\chi}_1^0$ that each decay to a Z or Higgs boson along with a $\tilde{G}$. Each of the $\tilde{\chi}_1^0$ is required to decay to a Higgs (Z) boson which decays to a diphoton (dielectron) final state. The other $\tilde{\chi}_1^0$ is not considered in the signal signature, and the Higgs/Z boson decays with the SM branching ratio. Since this search focuses on the cross section of the $\tilde{\chi}_1^0$ pair production, the production mechanism is largely irrelevant. The production of the $\tilde{\chi}_1^0$ sparticle with its subsequent decay to an SM Higgs/Z boson producing a diphoton/dielectron final-state signature is of importance for this search.

Figure 3.5 shows for 13 TeV pp collisions the total production cross section of the GMSB model as a function of the NLSP mass. The cross section is computed at next-to-leading order (NLO) and at next-to-logarithmic (NLL) precision in the limit of the mass degenerate Higgsino, $\tilde{\chi}_1^0$, $\tilde{\chi}^\pm$, and $\tilde{\chi}_2^0$ with all other sparticles assumed to be heavy and decoupled [74, 75].

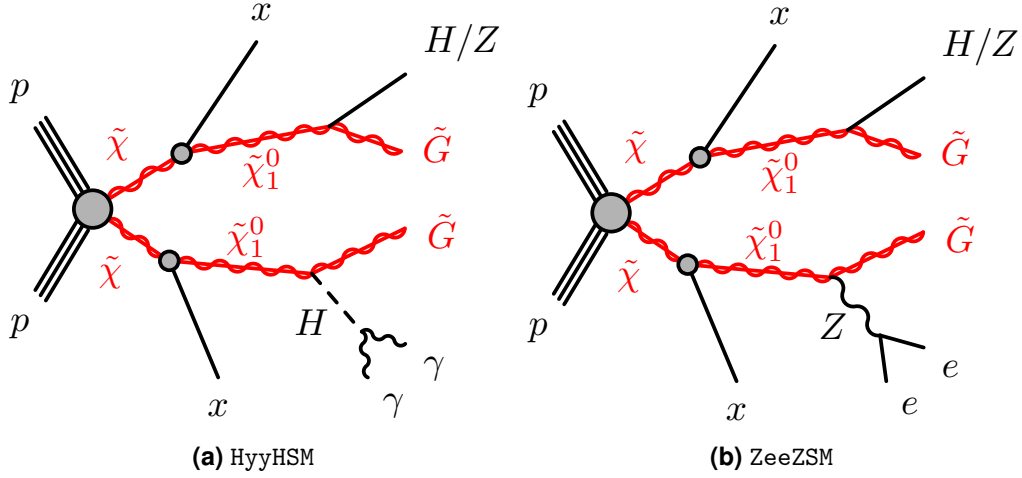


Figure 3.4: Feynman diagrams for the signature of the signal process of the considered GMSB model. The signal signature consists of the pair-production of $\tilde{\chi}_1^0$ that each decay to a Z or Higgs boson along with a $\tilde{G}$. Each of the $\tilde{\chi}_1^0$ is required to decay to a Higgs (Z) boson as shown in the left (right) which decays to a diphoton (dielectron) final state. The other $\tilde{\chi}_1^0$ is not considered in the signal signature, and the Higgs/Z boson decays with the SM branching ratio. The signal signature with the diphoton final state is dubbed HyyHSM and the dielectron final state is dubbed ZeeZSM.

The lifetime of the NLSP, which depends on the fundamental SUSY breaking scale, and the mass of the NLSP are free parameters in this GMSB model. Figure 3.6 shows the distribution of the NLSP momentum in the plane transverse to the pp collision (p_T) 3.6a and the relativistic speed 3.6b for the $H + \tilde{G}$ decay mode shown in the Feynman diagram in Figure 3.4. The distributions are unit normalized, with the different colors representing the different NLSP masses. As evident from the distributions, for higher NLSP masses the p_T distribution becomes "harder", i.e., the distribution peaks at high values. The $\tilde{\chi}_1^0$ and $\tilde{\chi}$ are nearly degenerate, i.e., $m(\tilde{\chi}) = m(\tilde{\chi}_1^0) + 1 \text{ MeV}(m(\tilde{G}))$. As the mass of the $\tilde{\chi}$ increases, the $\tilde{\chi}_1^0$ boost increases which in turn makes the $\tilde{\chi}_1^0$ p_T distribution harder. Similarly, the β distribution becomes "softer" as the NLSP mass increases.

Of the two $\tilde{\chi}_1^0$ produced, we force the decay mode of one $\tilde{\chi}_1^0$ to be either $H + \tilde{G}$ or $Z + \tilde{G}$ with the subsequent decay of $H \rightarrow \gamma\gamma$ and $Z \rightarrow ee$. However, the other $\tilde{\chi}_1^0$ can decay to either a Higgs or Z boson which subsequently decays via SM decay modes. Thus, the final state signature consists of either two Higgs/Z bosons or

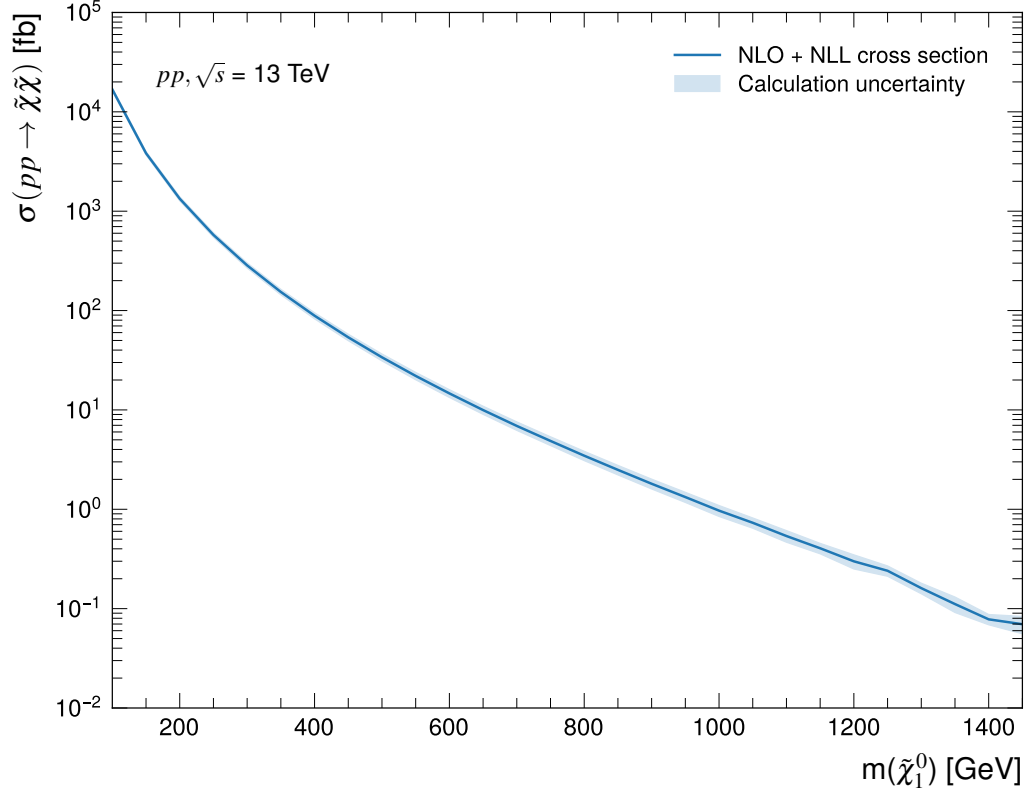


Figure 3.5: Production cross section calculation for pure Higgsino-like pair production assuming $\tilde{\chi}_1^0, \tilde{\chi}^\pm, \tilde{\chi}_2^0$ with degenerate mass $m(\tilde{\chi})$. The production cross sections are computed at next-to-leading-order (NLO) plus next-to-leading-log (NLL) precision in a limit of mass degenerate higgsino $\tilde{\chi}_1^0, \tilde{\chi}^\pm$, and $\tilde{\chi}_2^0$ with all the other sparticles assumed to be heavy and decoupled [74, 75].

a Higgs and a Z boson. For the sake of brevity, the four possible final states are named by the possible decay modes which either of the two Higgs/Z bosons can undergo. The boson which has a forced decay is named Hyy/Zee. Similarly, the boson which decays via SM modes is named HSM/ZSM. The four final states are thus called HyyHSM, ZeeZSM, HyyZSM, and ZeeHSM.

3.7 Previous search results

No previous search with this signal signature has been performed by the ATLAS or the CMS experiments. Previous ATLAS searches were performed for non-

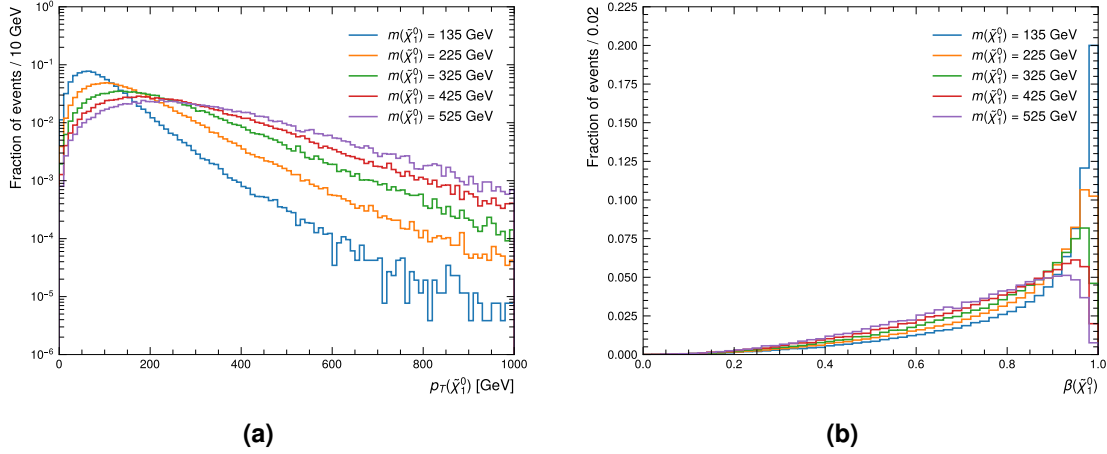


Figure 3.6: Transverse momentum (p_T) and relativistic speed (β) of the NLSP for several values of the NLSP mass. In these distributions, the NLSP decay mode of $H + \tilde{G}$ is considered.

pointing and delayed photons produced in the long-lived NLSP decays in the datasets of pp collisions collected at the center-of-mass energies of 13 TeV [76] during the data-taking years 2015–2018 of the LHC, and at both 7 [77] and 8 TeV [78] during the data-taking years 2011–2012. No search found excess over the SM background expectation, and set limits in the context of the studied GMSB SUSY models. A recent CMS [79] result searching for such models also found data agreeing with the SM prediction. These searches provide generic sensitivity to events that contain one or more non-prompt photons that do not necessarily originate from a common vertex, making this result the first to exploit the correlation between e/γ measurements that are expected from the GMSB delayed higgsino signal.

3.8 Summary

This chapter provided a brief introduction to Supersymmetry, the particle content of SUSY, the Minimal Supersymmetric Standard Model, and the phenomenology of softly-broken SUSY. The motivation of long-lived particles in the context of both the SM and SUSY theories was also presented. Later, this chapter described the Gauge Mediated SUSY Breaking model, which is one of the models to describe the soft-breaking of supersymmetry. In GMSB, the gravitino is the lightest super-

symmetric, and assuming R-parity conservation all sparticles will eventually decay to the stable gravitino. In this thesis, a particular GMSB model is considered, where the $\tilde{\chi}_1^0$ is the NLSP and is a mass eigenstate of the Bino, Wino, and Higgsino gauge eigenstates. The NLSP has a significant Higgsino or Wino component which results in $\mathcal{O}(1)$ branching ratio to $H + \tilde{G}$ and $Z + \tilde{G}$. The resulting H (Z) boson decays to $H \rightarrow \gamma\gamma$ ($Z \rightarrow ee$) decay mode, and since the NLSP is long-lived, the photons (electrons), produced from the cascade of the NLSP decay, have a displaced production vertex. In addition, these photons (electrons) have a non-zero time of arrival at the calorimeter, thereby making them delayed compared to those produced in the primary collision vertex. The search for a *displaced* and *delayed* electromagnetic objects has not yet been performed by the ATLAS or the CMS experiments.

This thesis provides a first search of delayed electromagnetic objects arising from a displaced vertex.

Chapter 4

The Large Hadron Collider

Despite my resistance to hyperbole,
the LHC belongs to a world that can
only be described with superlatives
...

Lisa Randall

*Knocking on Heaven's Door: How
Physics and Scientific Thinking
Illuminate the Universe and the
Modern World*

The Large Hadron Collider (LHC) recreates the high-energy environment which existed shortly after the Big Bang. LHC is one of the greatest engineering and physics marvels of the 21st century. Section 4.1 provides a brief introduction to the relevant concepts of accelerator physics. Section 4.2 describes the LHC accelerator complex, the experiments at the LHC, and the machine operation. Section 4.3 describes the operating conditions of the LHC during the data-taking years from 2015 to 2018.

4.1 Concepts of Accelerator Physics

In an accelerator, charged particles are accelerated under the influence of an electric field, in a stream called *particle beams*. Most modern particle accelerators provide bunched beams, containing packets, or *bunches*, of particles instead of a continuous stream. In a synchrotron accelerator, radio frequency (RF) cavities provide particle acceleration. The RF cavities provide an electromagnetic field that oscillates at an optimal frequency to provide acceleration to properly timed particle bunches. Particles passing through the RF cavities get bunched in the troughs of the oscillating electromagnetic wave; these troughs are called *RF buckets* [80]. In a circular accelerator, the particle bunches pass many times through the RF cavities to boost the particle energy each time it passes through the cavity.

The particles are kept in their trajectories by tuning the magnetic field provided by dipole magnets. Additional multipole magnets are used for the beam optics, focusing, and constraining the movement in the transverse direction.

As the particle moves along its nominal trajectory, s , it undergoes *betatron oscillations* in the transverse direction. The amplitude of these oscillations is described by the beta function, $\beta(s)$, which depends on the multipole configuration of the magnets. For a given position, s , the motion in the phase-space of the particle describes an ellipse of area $2\pi J_x$, where J_x is a constant and independent of s . For a beam with a Gaussian distribution in the phase space, the constant area, called *emittance* is defined as

$$\epsilon = \pi \frac{\sigma^2(s)}{\beta(s)} \quad (4.1)$$

Here, $\sigma(s)$ is the beam size in the transverse direction, which is the standard deviation of the Gaussian distribution. It is common practice to consider an energy-independent *normalized emittance*, denoted by ϵ_n , defined as

$$\epsilon_n = \frac{\beta_R \gamma_R}{\pi} \pi \frac{\sigma^2(s)}{\beta(s)} \quad (4.2)$$

Where, β_R , and γ_R are the usual relativistic functions.

One of the most important parameters of accelerators is the center-of-mass energy (*c.m.e.*), denoted by the symbol $\sqrt{s}$. For a collider with collisions of two beams of particles accelerated to the same energy, the c.m.e. is twice the beam energy $E_{cme} = 2E_b$. For a circular collider, the momentum and energy of the colliding beams with atomic charge, Z , is determined by the machine radius, ρ , and by the average magnetic field, B , of the dipole magnets.

$$E_b [\text{GeV}] = 0.3 \cdot Z \cdot B [\text{T}] \cdot \rho [\text{m}] \quad (4.3)$$

Normal conducting (NC) magnets can achieve a maximum field strength of 2 T. If one were to construct a circular accelerator, using NC magnets, for proton beams with a collision center-of-mass energy of 7 TeV, then the required machine radius would be $\rho \simeq 12$ km. Constructing a circular accelerator with such a large radius would be expensive and would also require high electrical power. Therefore, superconducting magnets are used in modern particle accelerators to remedy

the need for long accelerator rings and high magnet power consumption. The maximum attainable energy in a circular accelerator is also limited by synchrotron radiation. The total power radiated is inversely proportional to the fourth power of the particle mass. Therefore, for protons, the total power radiated is 10^{13} times lower than that for electrons. In the past synchrotron radiation wasn't a significant problem for proton accelerators. However, for the LHC the synchrotron radiation poses a challenge to the maintenance of the superconducting temperature and to the stability of the vacuum pressure [81].

Another important accelerator parameter is *luminosity*, $\mathcal{L}$, which describes the ability of an accelerator to provide the expected number of events, N_{exp} , for a given production cross section, σ_{exp} .

$$N_{\text{exp}} = \sigma_{\text{exp}} \int \mathcal{L}(t) dt \quad (4.4)$$

The integral in Equation 4.4 is called *integrated luminosity*, $\mathcal{L}_{\text{int}}$, and reflecting the smallness of production cross sections are reported in units of inverse femto- or attobarn, e.g., $1 \text{ ab}^{-1} = 10^{42} \text{ cm}^2$. The *instantaneous luminosity*, $\mathcal{L}(t)$, can be calculated using the accelerator characteristics. For a circular accelerator, the beams are made to collide at one or more *Interaction Points (IP)*. For an accelerator with two identical bunches with beam sizes that are approximately Gaussian, the instantaneous luminosity for head-on collisions is given by [9]

$$\mathcal{L} = f_{\text{rev}} n_b \gamma_R \frac{N^2}{4\pi\epsilon_n \beta^*} \mathcal{F} \quad (4.5)$$

Here, f_{rev} is the revolution frequency, n_b is the number of bunches per beam, N is the number of particles per bunch, ϵ_n is the normalized emittance, β^* is the beta function at the IP, γ_R is the relativistic γ function, and $\mathcal{F}$ is a geometrical factor arising from the fact that the beams do not collide head-to-head. Therefore, to obtain high luminosity, one needs a high number of bunches with high bunch populations and low emittance. However, achieving the ideal parameters which maximize luminosity is challenging.

The absolute calibration of machine-delivered luminosity is not performed during data-taking since the measurement can cause undesired interference. In

addition, the determination of the luminosity using beam parameters (Eq. 4.5) is not very accurate, with $\sim 10\%$ uncertainty on the measurement. Specialized runs called the "*van der Meer scans*" [82] are performed to calibrate luminosity-sensitive detectors and to provide an absolute measurement of the luminosity. In the van der Meer scan, the two beams are separated from each other in the transverse direction, and the resulting event rates are measured as a function of this separation [82]. The absolute luminosity can be computed using the rate of inelastic scattering, R_{inel} , and the cross section of the inelastic scattering, σ_{inel}

$$\mathcal{L} = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}} = \frac{\mu n_b f_{\text{rev}}}{\sigma_{\text{inel}}} \quad (4.6)$$

Here, f_{rev} is the revolution frequency, n_b is the number of particle bunches, and $\mu = \left\langle \frac{N_{\text{inel}}}{n_b} \right\rangle$ is the *average number of inelastic interactions per bunch crossing*. The quantity μ is also called *pileup*.

4.2 The Large Hadron Collider

The Large Hadron Collider (LHC) [83], operated by the European Organization for Nuclear Research (CERN), is a 27 km long circular particle accelerator, placed about 100 m underground at the border of France and Switzerland. The LHC is designed to create high-energy particle collisions at the TeV energy scale; it is designed to perform proton-proton, proton-ion, and ion-ion collisions. These collisions occur at four different locations along the LHC ring; each of these locations houses a major particle detector. ATLAS [2] and CMS [84] are general-purpose detectors that probe a wide range of physical processes. LHCb [85] and ALICE [86] are specialized experiments designed to study *B*-physics and heavy-ion collisions, respectively.

The LHC is a two-ring-superconducting-hadron accelerator and collider constructed in the existing tunnel of the Large Electron Positron (LEP) collider, which was operational from 1989 to 2000. The basic layout of the LHC follows from the LEP tunnel geometry. The LHC has eight tunnel arcs and eight straight sections. Two beams circulate in opposite directions around the ring and are then steered into each other at the IPs. The eight straight sections contain various beam services such

as beam cleaning, injection, dump, and RF acceleration, as well as four experimental caverns at which beam collisions occur. The arcs contain dipole magnets which are used to steer the particles in a circular orbit. A schematic layout of the LHC is shown in Figure 4.1.

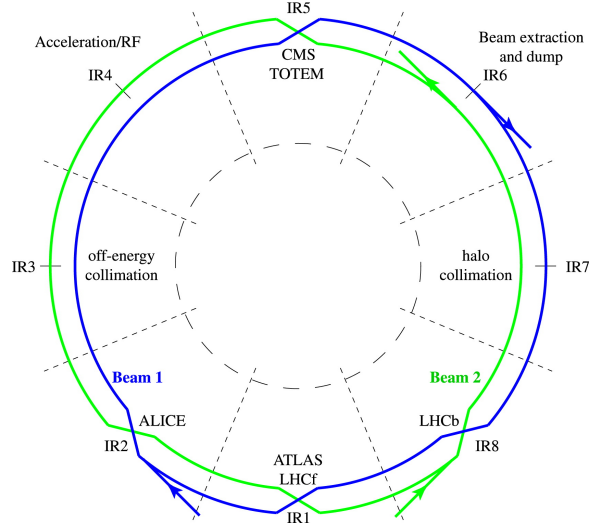


Figure 4.1: Schematic layout of the LHC with its 8 arc sections, two-beam design, and its four experimental insertions [6].

Circular colliders such as the LEP or the Tevatron, which collide particle-anti-particle beams, can have an efficient design that utilizes the same beamline for the two counter-rotating beams. In contrast, for the LHC, two beamlines would be required. Due to the limited space in the LHC tunnel, a novel twin-bore magnet design [87, 88] was adopted. The twin-bore dipole magnet provides a uniform magnetic field with opposite directions while sharing the same cold vessel. The dipole magnets use coils made of Niobium-Titanium superconducting cables which are cooled to 1.9 K, using superfluid helium, and provide a field of 8.33 T. The LHC uses 1,232 dipole magnets to bend the beam and 392 quadrupole magnets for focusing. Several other types of magnets complete the beam optics system.

The LHC acceleration complex, shown in Figure 4.2, is described briefly below. The acceleration and collision steps are *injection*, *ramp*, *squeeze and adjust*, *stable beams*, and *dump and ramp down*.

Protons are obtained by stripping the electrons from molecular hydrogen gas and are initially accelerated to an energy of 50 MeV by the LINAC4 accelerator.

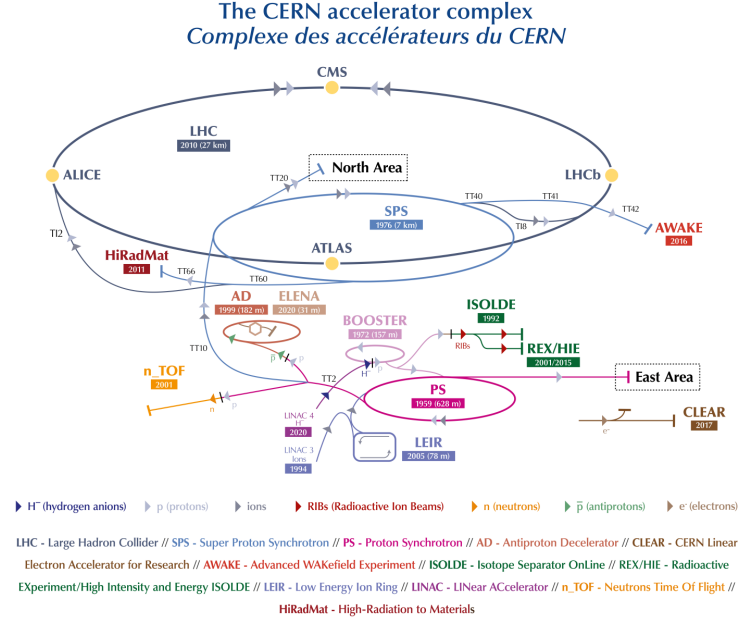


Figure 4.2: Schematic of the CERN accelerator complex and the relative positions of the experiments. The series of machines that constitute the LHC accelerator chain, as well as additional setups for non-LHC experiments, are visible [89]

The protons are then fed into a series of synchrotrons with increasing energies, to be accelerated to the LHC injection energy of 450 GeV. From LINAC4, the protons beams are accelerated to an energy of 1.4 GeV in the four concentric rings of the Proton Synchrotron Booster. The protons from the Booster then get injected into the Proton Synchrotron (PS) where they are accelerated to an energy of 25 GeV. In the PS the protons are also assembled into a train of proton bunches which are approximately 25 ns apart and nominally contain 1.15×10^{15} protons per bunch. In the last step of the injection, four bunch trains from the PS are injected into the Super Proton Synchrotron (SPS). In the SPS, the proton bunches are accelerated to the injection energy of 450 GeV before being injected into one of the LHC rings. The entire procedure is repeated several times to fill up to 2,808 bunches in one LHC ring, assembled in bunch trains. Once the LHC ring is filled, the bunches are accelerated to an energy of 7 TeV which takes about 25 min.

Once the desired collision energy is reached, the beam optics are adjusted to reduce the beam sizes at the IPs (*squeeze*), and the beams are adjusted to be

optimally colliding (*adjust*). The *stable beams* phase is when the LHC conditions are stable, collisions take place at the IPs, and it is safe for detectors to be turned on to record collision data. Small adjustments such as β^* -leveling [90] and crossing-angle optimization [91] can be performed. The beam lifetime is 10–15 h after which the beams are dumped and a new LHC fill can start. Besides a programmed dump, beams can also be dumped either by a request from one or more experiments (in case of problems with the detector) or be an unplanned dump. The LHC operation cycle is represented pictorially in Figure 4.3.

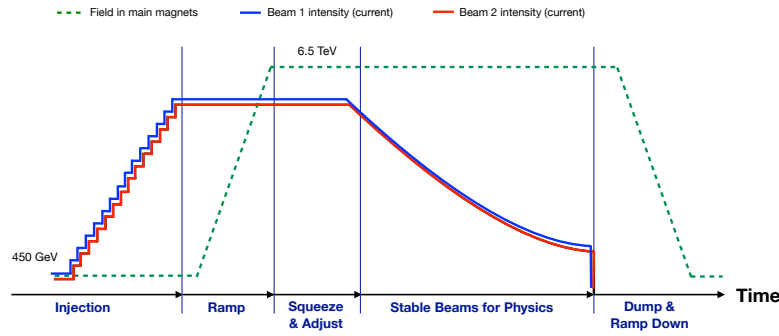


Figure 4.3: The LHC goes through a cycle composed of several phases: the injection of beams into the rings, the acceleration to the collision energy during ramp, the preparation of beams for collisions during squeeze and adjust, the phase where collisions take place during stable beams, the extraction of the beams from the rings during dump, and finally the ramping down of the magnetic fields [92].

The LHC radio frequency (RF) system provides longitudinal focusing which constrains the particle motion in the longitudinal phase space to a confined region called the RF bucket. The RF frequency is 400 MHz, which corresponds to 75 cm wavelength or buckets of 2.5 ns length. Although the LHC circumference is 35,640 RF wavelengths which could theoretically allow for the same number of filled buckets, a more realistic bunch spacing for the LHC is one bunch per 10 RF buckets or 25 ns. The minimum bunch spacing corresponds to a maximum bunch crossing

frequency of 40 MHz—the data rate at which all detectors at the LHC are designed to collect data. Empty bunch crossings where no collisions occur are used by the experiments to estimate the events due to non-collision backgrounds.

During the filling of the main LHC bunches, so-called "*satellite bunches*" can be populated, wherein protons are captured and accelerated within more finely spaced RF buckets [93]. These satellite bunches can cause pp collisions that can be recorded as part of the ATLAS data sample. Since ATLAS uses a 400 MHz RF system, satellite bunches would be, in principle, expected to be separated by the main bunch at integer multiples of ± 2.5 ns. However, satellite bunches at integer multiples of ± 5 ns are more populated than those at multiples of ± 2.5 ns. The cause of this asymmetric filling can be attributed to the injection of the bunches in the SPS, which is operated with a 200 MHz RF system. Although the population of the satellite bunches at ± 5 ns are reduced by a factor of 10^3 compared to the population of the main bunches, the "satellite-satellite" collisions are of interest for this thesis. Section 8 explains in detail how the pp collisions produced in satellite bunches produce an observable effect on the photon timing distributions.

4.3 Operating Conditions in Run 2

Between 2015 and 2018 the LHC operated with protons at beam energies of 6.5 TeV, with an integrated luminosity of 160 fb^{-1} ; the operation of the LHC during these years is called Run 2. The peak proton performance exceeded twice the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A range of different rates of integrated luminosity and pileup conditions were observed because of various operational reasons, and improvements in beam operations. Figure 4.4 shows the cumulative integrated luminosity provided by the LHC, recorded by the ATLAS experiment, and the fraction of the ATLAS-recorded data which is considered "good for physics". The recorded luminosity reflects the data-acquisition (DAQ) inefficiency, as well as the inefficiency of the so-called "warm start" of the tracking detectors. The data-quality assessment requires, at minimum, the proper functioning of all the subsystems of the ATLAS experiments. Therefore, accounting for the inefficiencies of the DAQ, the warm start, and the data-quality assessments, the ATLAS experiment recorded a total of 139 fb^{-1} of data during Run 2.

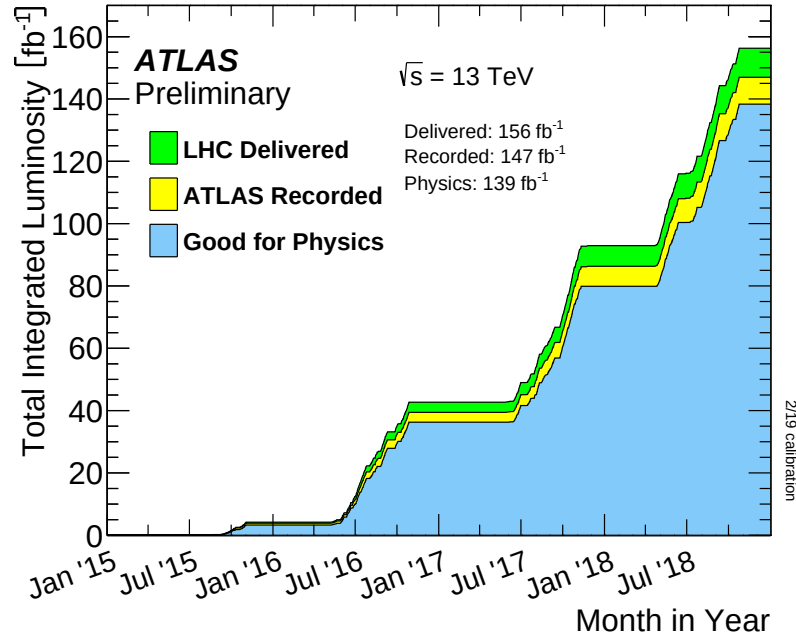


Figure 4.4: Cumulative luminosity versus time delivered to ATLAS (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams for pp collisions at 13 TeV center-of-mass energy in 2015–2018. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests ATLAS to put the detector in a safe standby mode to allow a beam dump or beam studies. The recorded luminosity reflects the DAQ inefficiency, as well as the inefficiency of the so-called "warm start": when the stable beam flag is raised, the tracking detectors undergo a ramp of the high-voltage and, for the pixel system, turn on the preamplifiers. The All Good Data Quality criteria require all reconstructed physics objects to be of good data quality.

Another important parameter for particle collisions is the average number of interactions per bunch crossing or pileup, μ . Figure 4.5 shows the luminosity-weighted distribution of the mean number of interactions per crossing for 2015–2018. The increase in the average pileup value from 2015 to 2018 was achieved due to improvements in the LHC machine and the detectors.

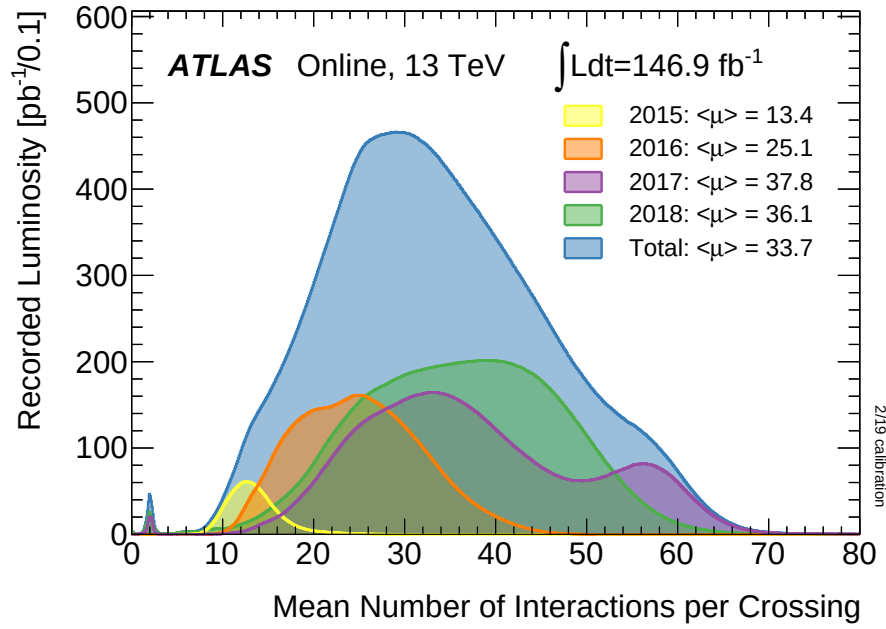


Figure 4.5: Shown is the luminosity-weighted distribution of the mean number of interactions per crossing for the 2015–2018 pp collision data at 13 TeV center-of-mass energy. All data recorded by ATLAS during stable beams are shown, and the integrated luminosity and the mean μ value are given in the figure. The mean number of interactions per crossing corresponds to the mean of the Poisson distribution of the number of interactions per crossing calculated for each bunch.

Chapter 5

The ATLAS Experiment

But what would be our readers' reaction if we simply refused to get to the bottom of that question?

Thomas Mann
The Magic Mountain

ATLAS (A Toroidal LHC ApparatuS) is the largest of the four experiments at the LHC. Section 5.1 provides an overview of the ATLAS detector, outlining the dimensions and the geometry. Sections 5.2–5.7 provide an overview of each subsystem of the ATLAS detector. Since this thesis presents a search for electromagnetic objects, a comprehensive summary of the ATLAS calorimetry is provided in Section 5.3. A detailed description of the detectors and their performance are available in Ref. [2].

5.1 Overview of the ATLAS Detector

ATLAS is a general multipurpose detector designed to record collision data from proton-proton (pp), ion-ion (A - A), or proton-ion (p - A) beams. The detector is designed to exploit the full discovery potential of the LHC and to be sensitive to a broad range of physics processes. The broad range of physics opportunities and the challenging environment of the LHC impose severe requirements for the detector in terms of performance and operation in a radiation environment.

The ATLAS detector has a cylindrical geometry that is forward-backward symmetric with respect to the interaction point. The dimensions of the detector are 25 m in height and 44 m in length, as shown in Figure 5.1. The ATLAS detector is composed of several concentric detectors and systems. The innermost detector, which is immersed in a solenoidal magnetic field, is the Inner Detector (ID) system. The ID consists of the Pixel Detector, the SemiConductor Tracker (SCT), and the Transition Radiation Tracker (TRT). The Calorimeters surround the solenoid system and consist of the Liquid Argon (LAr), the Hadronic, the Forward, the Endcap, and

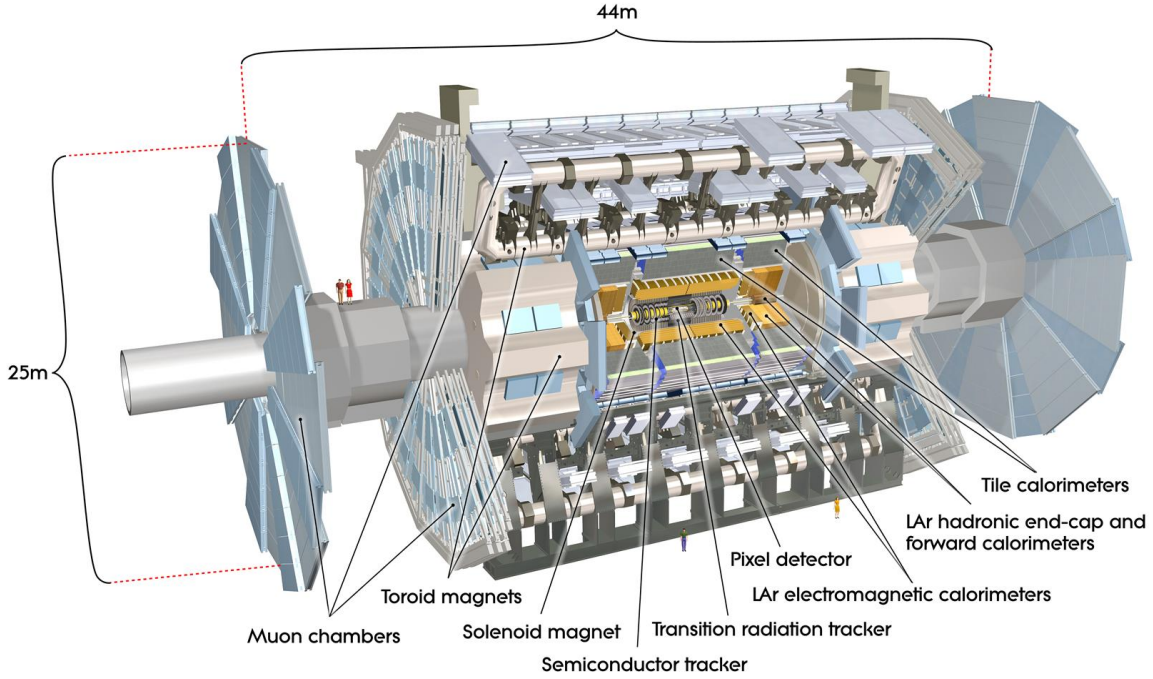


Figure 5.1: Cut-away view of the ATLAS detector [7].

the Tile calorimeter. The calorimeter system is surrounded by muon spectrometers. The muon spectrometers are housed in an air-core toroid system. The detector is complemented by a complex and sophisticated Trigger and Data Acquisition (TDAQ) system.

The right-handed coordinate system of ATLAS is depicted in Figure 5.2. The interaction point (IP) is considered to be the center of the detector, and the coordinate system where $x = y = z = 0$. The positive x -axis is defined as pointing towards the center of the LHC ring from the IP. The positive y -axis is defined as pointing upwards. The positive z -axis is in the direction of the beam and is perpendicular to both the x - and the y -axis. The side-A of the detector is defined with respect to the positive z -axis and side-C is defined with respect to the negative z -axis. The azimuthal angle, ϕ , is measured around the beam axis in the x - y plane. The polar angle, θ , is the angle from the beam axis. The pseudorapidity, η , is more commonly

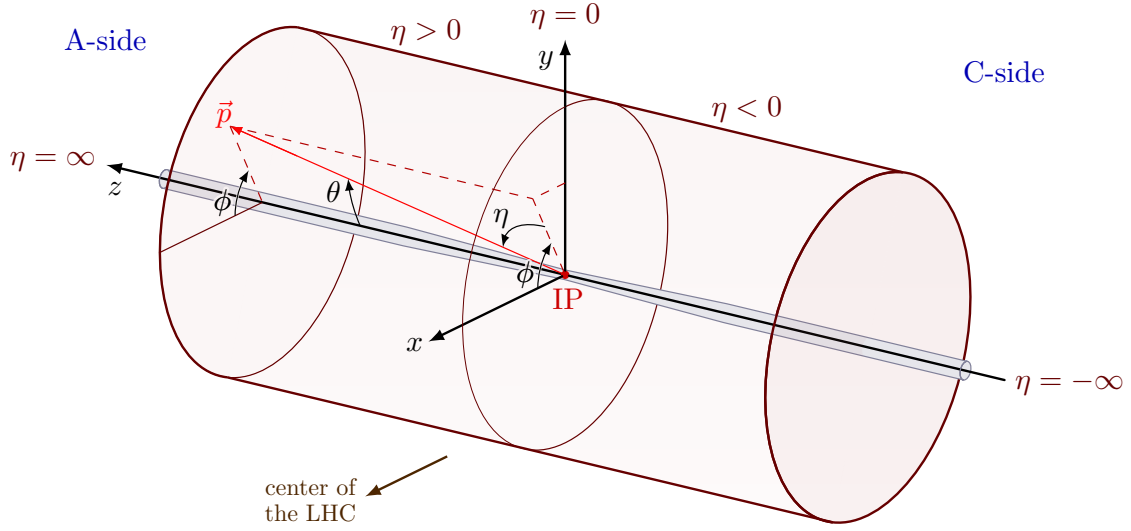


Figure 5.2: Illustration of the ATLAS coordinate system with a cylindrical detector.

used than the polar angle. Pseudorapidity is defined as

$$\eta \equiv -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) \quad (5.1)$$

The distance in pseudorapidity-azimuthal angle space, ΔR , is defined as

$$\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2} \quad (5.2)$$

The general performance goals of the various ATLAS detectors are listed in Table 5.1. The performance goals are listed for the η coverage where the detector measurements are possible, and for the coverage where the ATLAS detectors provide information to the first level of the trigger system.

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
Barrel and End-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 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 5.1: General performance goals of the ATLAS detector. Note that, for high p_T muons, the muon-spectrometer performance is independent of the inner-detector system. The units for E and p_T are in GeV.

5.2 Inner Detector

The Inner Detector (ID) [94–96] provides reconstruction, above a given momentum threshold, of the momentum and trajectory of tracks of charged particles produced in the collision. The reconstructed tracks are used to identify a set of common track intersection points along the beamline. From the intersection points, the positions of the primary vertex (PV) candidates are measured. The ID also provides electron identification over $|\eta| < 2.0$ and a wide range of energies between 0.5–150 GeV. The ID is able to provide a measurement of the z -position of the primary vertex with at least four tracks with a resolution of about 1 mm [94]. In addition to measuring the PV, the ID also provides a measurement of the decay vertex of long-lived particles which decay within the ID and produce a *secondary vertex*. The secondary vertex, along with several other parameters, is used to identify b quarks from c and other light-flavor quarks.

The ID is a series of cylindrical detectors with a diameter of 2.1 m and length of 6.2 m immersed in a solenoidal magnetic field of 2 T. The ID consists of a barrel section and two endcap sections with a total pseudorapidity coverage up to $|\eta| < 2.5$. A cut-away view of the ID is shown in Figure 5.3.

The innermost sub-detector of the ID is the Pixel detector, which consists of three concentric barrels and four disks on each side that are perpendicular to the beam axis. The pixel detectors also have the highest granularity since these detectors

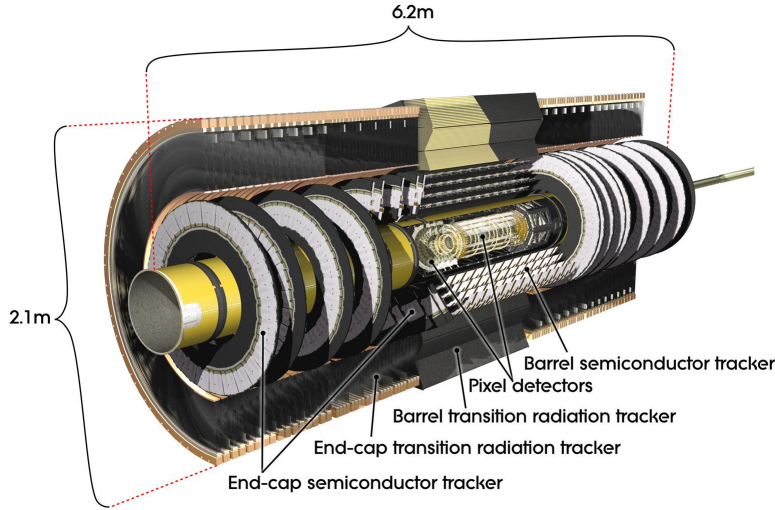


Figure 5.3: Cut-away view of the ATLAS Inner Detector

are closest to the beamline and the interaction point. The pixel detectors consist of about 80 million readout channels. The pixel sensors are segmented in $R - \phi$ and z , with a minimum pixel size in $R - \phi \times z$ of $50 \times 400 \mu\text{m}^2$. The intrinsic accuracies¹ in the barrel and the endcap disks are $10 \mu\text{m}$ ($R - \phi$) and $115 \mu\text{m}$ (z). The three barrel layers are located at $R_1 = 50.5 \text{ mm}$, $R_2 = 88 \text{ mm}$, and $R_3 = 122.5 \text{ mm}$. The endcap disks are located at $|z_1| = 473 \text{ mm}$, $|z_2| = 635 \text{ mm}$, $|z_3| = 776 \text{ mm}$, and $|z_4| = 1072 \text{ mm}$. Given the layout of the pixel detectors, a track typically consists of three pixel layer hits. Since the first barrel layer is closest to the beamline and is important for the b -tagging algorithm, it is typically called the B -layer.

In 2014, an *Insertable B-layer (IBL)* [97] was installed to be the innermost pixel layer. The IBL was installed at a radius of 33.0 mm from the beam axis to improve the tracking performance in the high luminosity environment of Run 2. Located between the beam pipe and the first pixel layer, the IBL adds one redundant hit in this critical small-radius region. The IBL consists of 6 million pixel readout channels. The size of the pixel sensors is $50 \times 250 \mu\text{m}^2$, which is 60% of the pixel size used for the other three layers. The intrinsic accuracies are $10 \mu\text{m}$ ($R - \phi$) and $75 \mu\text{m}$ (z).

The second sub-detector of the ID is the SCT detector, which consists of four concentric barrels and nine disks on each side that are perpendicular to the beam

¹The accuracy is defined as the pitch/ $\sqrt{12}$.

axis. The four barrel layers are located at $R_1 = 300$ mm, $R_2 = 373$ mm, $R_3 = 447$ mm, and $R_4 = 520$ mm. The nine endcap disks on each side are located at positions ranging from $|z| = 853.8$ mm to $|z| = 2720.2$ mm. The SCT is made of silicon microstrip sensors, with 6.3 million readout channels. Each barrel layer is tiled with square modules whereas each endcap layer is tiled with trapezoid-shaped modules. Each module consists of two layers of sensors of 6.16 cm of active silicon corresponding to 768 strips of 80 μm pitch. The two layers are arranged to provide a sensor pair with a stereo rotation of 40 mrad. In the barrel modules, the strip sensors are mounted so that one side has strips parallel to the beam axis with intrinsic accuracies of 17 μm ($R - \phi$) and 580 μm (z). In the endcap disks, the strip sensors are radially mounted with intrinsic accuracies of 17 μm ($R - \phi$) and 580 μm (R).

The third sub-detector of the ID is the TRT which consists of about 350,000 gas-filled straw tubes of diameter 4 mm. Each straw is filled with a $\text{Xe}/\text{CO}_2/\text{O}_2$ gas mixture with a wire anode through the center to collect the ionized particles from interactions between incident charged particles and the gas. The TRT only provides $R - \phi$ information with an intrinsic resolution of 130 μm . In the barrel, the straws are 144 cm long and are arranged parallel to the beam axis. In the endcaps, the straws are 37 cm long and are arranged radially in wheels. A typical track measurement in the TRT consists of at least 36 hits and provides tracking up to $|\eta| = 2.0$. Besides continuous tracking, the TRT also enables good separation between electrons and pions. When charged particles pass through the layers of plastic between the straws, they lose energy due to transition radiation and ionization. Transition radiation arises when ultra-relativistic particles cross the boundary between media with different dielectric constants [98]. The probability of a given particle emitting transition radiation is determined by its Lorentz- γ factor. Therefore, electrons, which are lighter than pions and thus have a higher γ factor, emit more transition radiation. The TRT straws are read out at two thresholds. Electrons passing the TRT will emit more radiation and thus produce more high-threshold hits.

The use of high-resolution detectors at smaller radii and continuous tracking elements at larger radii provides a precise measurement of the ϕ and z coordinates and robust pattern recognition.

5.3 Calorimetry

The ATLAS Calorimeter system, shown in Figure 5.4, provides a measurement of the energy and position of particles and provides particle identification. Besides measuring the deposited energy, the calorimeter system also provides a precise measurement of missing transverse energy. To meet the performance goals listed in Table 5.1, the calorimeters are designed to measure a 100 GeV electromagnetic (EM) energy deposition with a resolution on the order of 1%, depending on the η . Similarly, the hadronic energy deposit of 100 GeV should be measured with a resolution of $\sim 6\%$.

The calorimeter system covers a pseudorapidity range of $|\eta| < 4.9$, with different detectors suited to the requirements of the varying physics process of interest and to the radiation environment over the η -range. In the η -region matched with the ID, the fine granularity of the EM calorimeter provides precision measurements of the electrons and photons. The coarser granularity of the Hadronic calorimeters is sufficient to reconstruct hadronic energy deposits and to calculate missing transverse energy.

Calorimeters should contain the electromagnetic and hadronic energy depositions, called showers, and must also limit punch-through into the muon spectrometer. Therefore, the total thickness of the EM calorimeter is larger than 22 radiation lengths (X_0) in the barrel and larger than $24X_0$ in the endcaps. In terms of interaction lengths (λ), the total thickness is 11λ at $\eta = 0$.

Sampling calorimeters with Liquid Argon (LAr), as the sampling medium is used for the detection of EM, objects up to $|\eta| 3.2$, as well as hadronic objects in the $|\eta|$ range of 1.5–4.9. Hadronic calorimetry within $|\eta| < 1.7$ is provided by a steel/scintillator-tile calorimeter (TileCal).

5.3.1 Liquid Argon Calorimeter

LAr calorimeter consists of one barrel and two endcap systems. The EM calorimetry is provided by the EM barrel (EMB) up to $|\eta| < 1.475$, and EM endcaps (EMECs) in the region $1.375 < |\eta| < 3.2$. Besides the EM calorimeter, the endcaps also house the hadronic calorimeter (HEC) in the region $1.5 < |\eta| < 3.2$, and the forward calorimeter in the region $3.1 < |\eta| < 4.9$. An additional LAr presampler

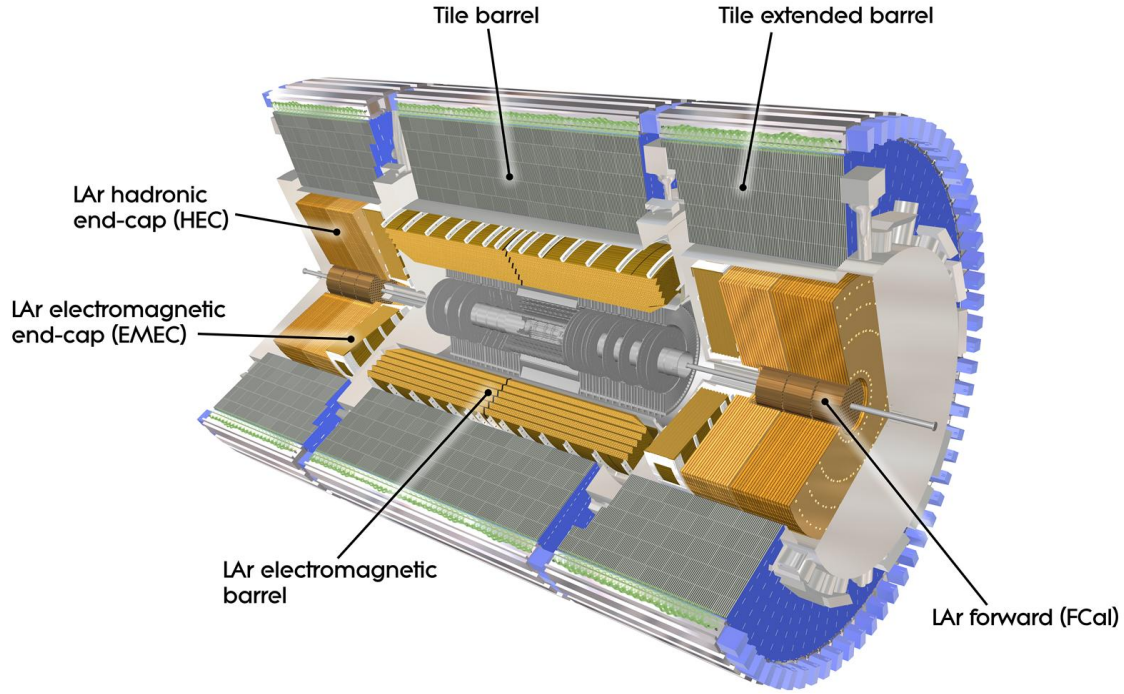


Figure 5.4: Cut away of the ATLAS calorimeter system with the different detectors labeled [2].

(PS) in the region $|\eta| < 1.8$ allows for corrections of energy losses in the material upstream to the LAr calorimeter.

The EMB [99] consists of two half-barrels, housed in the same cryostat. One half-barrel covers the region $0 < \eta < 1.475$ and the other half-barrel covers the region $-1.475 < \eta < 0$. Each half-barrel is 3.2 m in length and has an inner (outer) diameter of 2.8 m (4 m). The EMEC [100] consists of two wheels, one on each side of the EMB. Each wheel is 63 cm thick and has an inner (outer) diameter of 0.66 m (4.2 m). The EMEC wheels are contained in independent endcap cryostats, together with the HEC and FCAL. Each endcap calorimeter consists of two co-axial wheels, with the inner wheel covering the region $2.5 < |\eta| < 3.2$ and the outer wheel covering the region $1.375 < |\eta| < 2.5$.

The EM calorimeters are accordion-shaped copper-kapton electrodes housed between lead absorber plates and kept in position by honeycomb spacers, as shown in Figure 5.5. An incident particle produces a shower in the absorber material

which ionizes the LAr. In presence of an electric field, the electrons drift toward the readout electrode which produces a triangular pulse as shown in Figure 5.6. In the EMB, the size of the drift gap on each side of the electrode is 2.1 mm which corresponds to a total drift time of 450 ns at an operation voltage of 2000 V. In the EMEC, however, the drift gap is not constant but varies as a function of the radius and therefore the high-voltage varies as a function of η to provide a uniform detector response [2]. Each module of the EMB and the EMEC outer wheel has three layers with different granularities at different depths. In contrast, the EMEC inner wheel modules have only two layers. The EM calorimeter is designed such that the largest fraction of energy is collected in the second (middle) layer. A sketch of the barrel module with the different layers is shown in Figure 5.7.

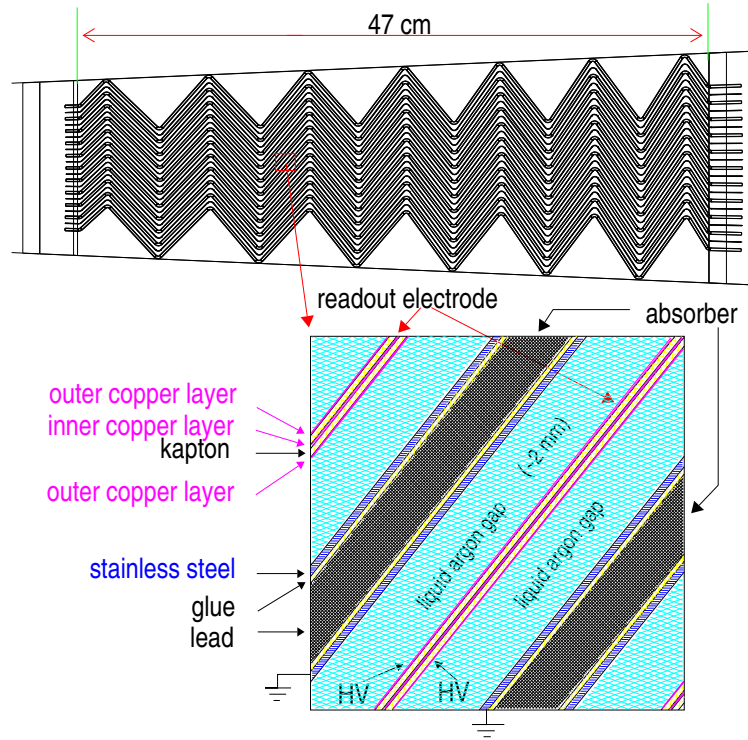


Figure 5.5: Accordion geometry of the EMB in a plane transverse to the LHC beams [8].

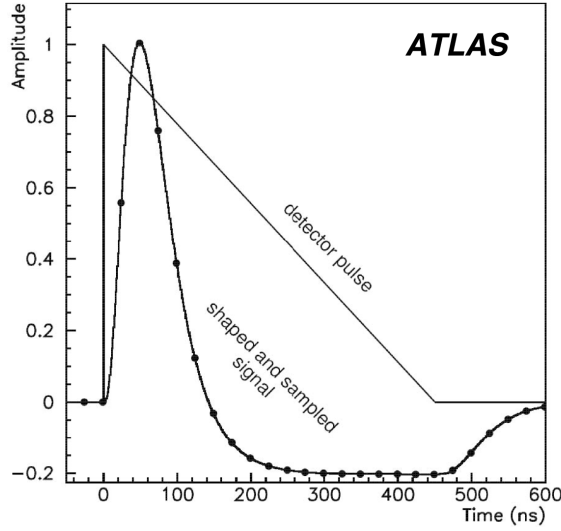


Figure 5.6: Shapes of the LAr calorimeter current pulse in the detector and of the signal output after bipolar shaping. The dots indicate an ideal position of samples separated by 25 ns [1].

The granularity in $\Delta\eta \times \Delta\phi$ of the EM cells is listed in Table 5.2. The first layer has a fine granularity to allow for the rejection of π^0 meson up to energies of 50 GeV or more. In addition to π^0 rejection, the fine segmentation of the first layer and the projective tower geometry can be exploited to construct the direction, *pointing*, of neutral particles such as photons, for which ID tracks do not exist. The measurement of the photon pointing was used to improve the resolution of the mass width of the Higgs boson decay to two photons ($H \rightarrow \gamma\gamma$). The calculation of a common vertex of a pair of photons using the fine segmentation of the first layer of the LAr EM calorimeter is fully exploited in this thesis.

The HEC consists of wedge-shaped, copper parallel-plate electrodes arranged in two wheels in each endcap. The HEC provides coverage for hadronic showers in the region $1.4 < |\eta| < 3.2$. The HEC is housed in the same cryostat as the EMEC and the FCAL detectors. Each HEC wheel is made of 32 wedge-shaped modules. The outer wheel radius is 2.03 m while the inner wheel radius is 372 mm for the first nine plates and 475 mm for all other plates. The first wheel is built out of 25 mm plates, while the second one used 50 mm plates. In both wheels the 8.5 mm gap is kept between the plates and three electrodes divide into four drift spaces of about 1.8 mm. The cells in the wheels are projective in ϕ but only "pseudo-

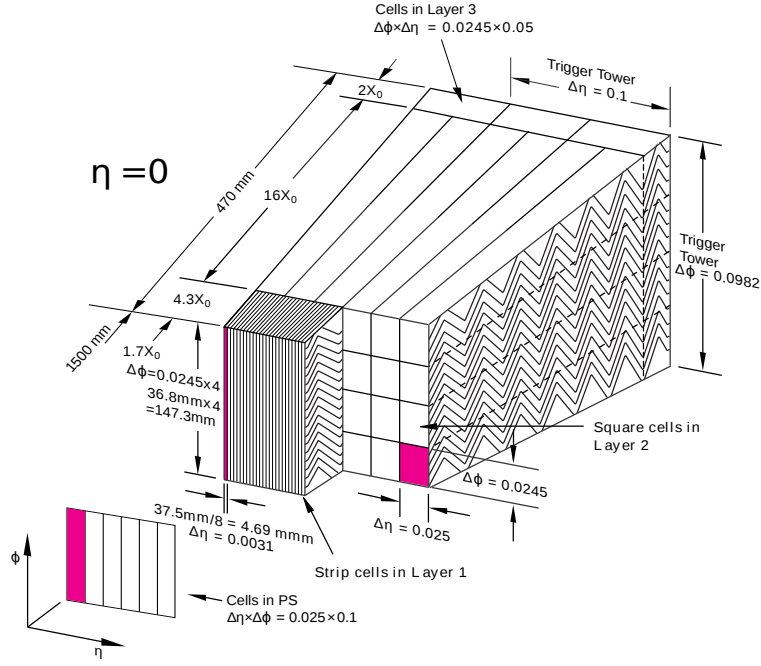


Figure 5.7: Sketch of the EMB module where the different layers are visible. The granularity in η and ϕ of the cells of each of the three layers is also shown [1].

Layer	η range				
	0.0–1.4	1.4–1.8	1.8–2.0	2.0–2.5	2.5–3.2
Presampler	0.025×0.1	0.025×0.1	-	-	
Front	0.003×0.1	0.003×0.1	0.004×0.1	0.006×0.1	0.1×0.1
Middle	0.025×0.025	0.025×0.025	0.025×0.025	0.025×0.025	0.1×0.1
Back	0.050×0.025	0.050×0.025	0.050×0.025	0.050×0.025	
Readout channels	110,208	25,600	12,288	24,064	1792

Table 5.2: Granularity in $\Delta\eta \times \Delta\phi$ of the EM cells [1].

pointing" in η . The cells have a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ up to $|\eta| = 2.5$ and $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ up to $|\eta| = 3.2$.

The FCAL [101] consists of three modules where each module consists of a metal matrix, with regularly placed longitudinal channels. The first module is made of copper and the other two are made of tungsten. The longitudinal channels are filled with the electrode structure consisting of concentric rods and tubes parallel to the beam axis. The LAr gap is designed to be small to reduce the ion build-up at high collision rates. The first module, called FCAL1, is designed for EM calorimetry, while the other two modules, called FCAL2 and FCAL3, respectively, are designed for hadronic calorimetry.

5.3.2 LAr Calorimeter Readout

The LAr readout electronics system is designed to record energies in a range from 50 MeV to 3 TeV for $\sim 182,000$ channels, with the required energy resolution listed in Table 5.1.

Ionized signals from the calorimeter cells are sent via feed-throughs to the on-detector (Front-End) crates which house the Front-End Boards (FEBs) [102]. One FEB receives signals from up to 128 cells which are amplified, shaped, digitized, and transmitted via optical fibers to off-detector (Back-End) electronics housed outside the experimental cavern. The signal from one cell is amplified and split into three overlapping gain (Low, Medium, and High) scales in the ratio 1/10/100. For each gain, the triangular pulse, shown in Figure 5.6, is shaped with a bipolar $CR - (RC)^2$ analog filter to optimize the signal-to-noise ratio. The shaped signals are then sampled at the bunch crossing frequency, 40 MHz, by a four-channel Switched Capacitor Array (SCA) analog buffer while waiting for an accept signal by the Level-1 trigger (cf. Section 5.7). For events accepted by the L1 trigger, the optimal gain is selected for each channel, and the samples are digitized and transmitted. For Run 2, four samples were digitized for each pulse. A schematic block diagram of the LAr readout electronics architecture is shown in Figure 5.8.

Besides the FEBs, the front-end crates also house additional boards. The calibration board [103] injects the ionization signal with a precise amplitude to mimic a range (~ 50 MeV to 3 TeV) of calorimeter energy deposit. The calibration system calculates the electronics gain for each channel, i.e., the conversion from ADC

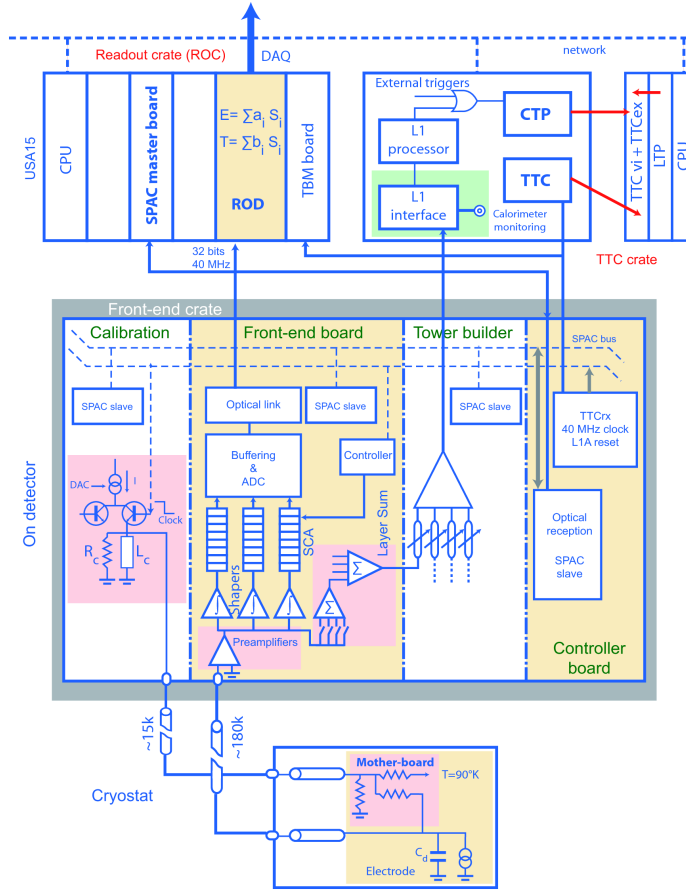


Figure 5.8: The schematic block diagram of the current LAr readout electronics architecture. The LAr ionization signal proceeds upwards, through the FE crates mounted on the detector to the BE electronics in the USA15 counting room. This diagram is valid for the EM calorimeters; slight changes would be needed to describe the HEC and FCal which include additional electronics inside the endcap cryostat.

counts to current, and monitors its evolution to ensure uniform response of the calorimeter. Signals to be sent to Level-1 (cf. Section 5.7) are formed by analog sums of cell signals from the PS, Front, Middle, and Back layers. The analog summed signals, called *Trigger Towers*, have a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ up to $|\eta| < 2.5$ and a granularity of $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ for $|\eta| > 2.5$. The Tower Builder Board [104] performs the analog summation of cell signals which make up the Trigger Tower and sends the summed signals to the Level-1 trigger. The Controller board [105] receives the *Trigger and Timing Control (TTC)* and the *Serial Protocol for ATLAS Calorimeter (SPAC)* [106] signals and distributes them to the front-end boards.

The *Embedded Local Monitoring Boards* [105] monitor the voltage and current values of the FEBs, water temperature, and low-voltage power.

5.3.3 Energy and Time Reconstruction

The cell energy and peaking time are reconstructed using the Optimal Filtering (OF) [107] technique. The off-detector electronics perform signal processing on the digitized calorimeter pulse to obtain the energy (E_{cell}) and the peaking time (t_{cell}) using the formulae

$$E_{\text{cell}} = F_{\mu\text{A} \rightarrow \text{MeV}} \times F_{\text{DAC} \rightarrow \mu\text{A}} \times \frac{1}{\frac{M_{\text{phys}}}{M_{\text{calib}}}} \times R \times \left[\sum_{n=1}^{N_{\text{samples}}} a_j(s_j - p) \right] \quad (5.3)$$

$$t_{\text{cell}} = \frac{1}{E_{\text{cell}}} \times \left[\sum_{n=1}^{N_{\text{samples}}} b_j(s_j - p) \right] \quad (5.4)$$

Here, E_{cell} is measured in MeV, t_{cell} is measured in ns. $F_{\mu\text{A} \rightarrow \text{MeV}}$ converts the ionization current to energy and $F_{\text{DAC} \rightarrow \mu\text{A}}$ is a property of the calibration board. $\frac{M_{\text{phys}}}{M_{\text{calib}}}$ is a factor to correct for the difference between the physics and the calibration signal. R is a factor obtained from calibration which converts the pulse ADC counts to DAC counts used to inject the calibration pulses. p is the pedestal value. The parameters a_j and b_j are Optimal Filtering Coefficients (OFCs), calculated using the method of Lagrange multiplier using the physics pulse and the noise auto-correlation matrix. A *Quality Factor*, Q^2 , calculated for each cell, quantifies the deviation of the observed pulse from the physics pulse as predicted by the calibration.

5.3.4 Tile Calorimeter

The Tile Calorimeter (TileCal) [108] is a sampling calorimeter using steel as the absorber and plastic scintillating tiles as the active medium. It is designed to absorb and measure the energy of hadronic particles. The TileCal consists of one barrel and two extended barrel sections covering the region $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$, respectively. The barrel is 5.8 m in length, and the two endcaps are 2.6 m in length; each section has an inner (outer) radius of 2.28 m (4.25 m). Each section consists of 64 modules, made of steel and scintillating tiles, shown in Figure 5.9

The scintillator tiles are oriented radially and normally to the beam line which allows for an almost seamless ϕ -coverage. The scintillators are read out on each of two sides by wavelength-shifting fibres, which are bundled to define cells and read out by photo-multiplier tubes (PMTs). Each cell is read out by two PMTs to provide redundancy in light read-out and improve spatial uniformity. Each module is segmented radially into three layers whose depth in interaction lengths are 1.5, 4.1, and 1.8λ , respectively, for the barrel, and 1.5, 2.6, and 3.3λ , respectively for the endcap. The read-out cell has a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the two innermost layers, and $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$ in the outer layer.

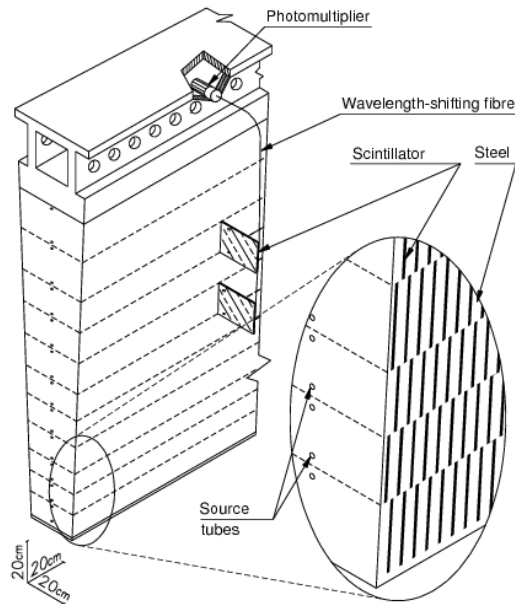


Figure 5.9: A sketch of one module of the tile calorimeter, showing alternating steel and scintillating material [2].

5.4 Muon Spectrometer

The Muon Spectrometer (MS) forms the outer part of the ATLAS detector and is designed to detect charged particles exiting the barrel and endcap calorimeters and to measure their momentum in the pseudorapidity range $|\eta| < 2.7$. It is designed to provide momenta measurement with a resolution of approximately 10% for 1 TeV tracks, which translates to a sagitta along the beam axis of 500 μm to be measured with a resolution better than 50 μm . It is also designed to trigger on the candidate muon tracks in the pseudorapidity $|\eta| < 2.4$.

The MS consists of several muon chambers located in the barrel and the endcap. The chambers in the barrel are located in three concentric cylindrical shells around the beam axis at radii 5 m, 7.5 m, and 10 m. In the two endcaps, the chambers form disks, or wheels, perpendicular to the beam axis and located at distances $|z| = 7.4$ m, 10.8 m, 14 m, and 21.5 m. The MS is immersed in a toroidal magnetic field which provides the deflection of the muon tracks. The toroid magnet configuration provides a field that is orthogonal to the muon trajectory and degrades the trajectory resolution due to multiple scattering. Depending on the radius and azimuth, the toroidal magnetic field varies from 0.15 T to 2.5 T in the barrel, and from 0.2 T to 3.5 T in the endcap.

To accommodate varying muon fluxes, there are four separate MS sub-detectors with varying design parameters tailored for different environments in different $|\eta|$ regions. The sub-detectors are the Monitored Drift Tubes (MDT), the Cathode Strip Chambers (CSC), the Resistive Plate Chambers (RPC), and the Thin Gap Chambers (TGC). A brief summary of the sub-detector parameters is shown in Table 5.3. A schematic view of the various sub-detectors is shown in Figure 5.10

Detector	Function	Coverage	# Chambers	# Channels
MDT	Precision tracking	$ \eta < 2.7$	1088	339,000
CSC	Precision tracking	$2.0 < \eta < 2.7$	32	31,000
RPC	Triggering	$ \eta < 1.05$	544	359,000
TGC	Triggering	$1.05 < \eta < 2.7$	3588	318,000

Table 5.3: Main parameters of the sub-detectors of muon spectrometer [2].

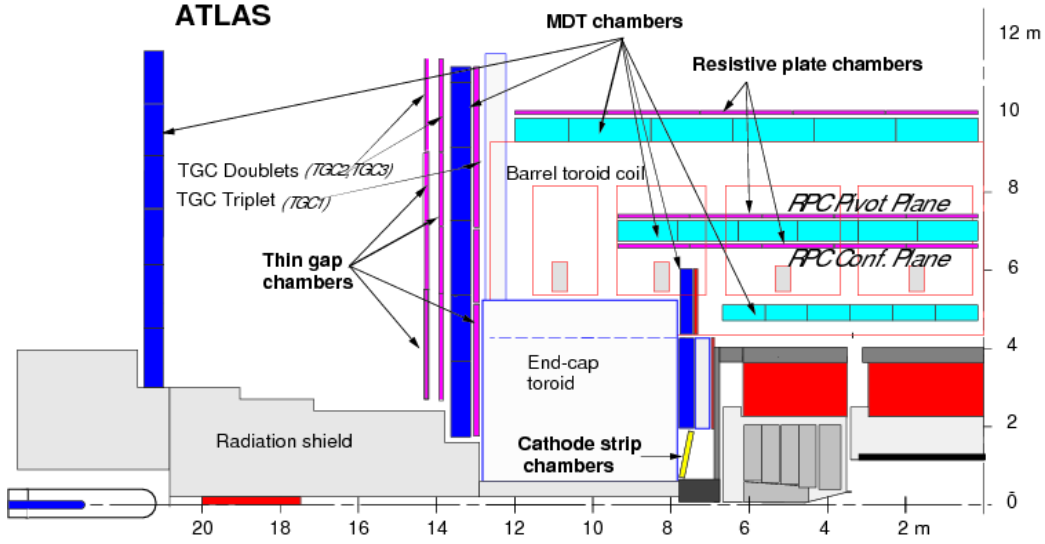


Figure 5.10: Schematic view of the MS in the y-z projection.

Precision momentum measurement is provided by the MDT and the CSC sub-detectors. The MDT chambers consist of three to eight layers of drift tubes, operated at an absolute pressure of 3 bar to achieve an average resolution of $80 \mu\text{m}$ per tube, or about $35 \mu\text{m}$ per chamber. The CSC chambers are multiwire proportional chambers with cathode planes segmented into strips in orthogonal directions. The orthogonal segmentation allows for the measurement of both the coordinates from the induced-charge distribution. The resolution of the chamber is $40 \mu\text{m}$ in the bending plane and 5 mm in the transverse plane.

The precision-tracking chambers are complemented by a system of fast trigger chambers with the ability to deliver track information within a few tens of nanoseconds. The RPCs, located in the barrel ($|\eta| < 2.1$), and the TGCs, located in the endcaps ($1.04 < |\eta| < 2.4$), provide the measurement of the coordinates of the track in the bending (η) plane and in the non-bending (ϕ) plane. Both chamber types deliver signals with a spread of 15–25 ns, thus providing the ability to tag the bunch crossing. After precise alignment of all the subsystems of the MS, matching of the hits from the precision-tracking and triggering parts of the muon system can be achieved with negligible probability for overlapping tracks from uncorrelated particles. In the correlated case, matching with inner detector tracks resolves the ambiguity.

5.5 Magnet System

The ATLAS magnet system consists of four large superconducting magnets. The magnet system is 22 m in diameter and 26 m in length with a field volume of approximately 12,000 m³. The magnet system consists of a solenoid and a barrel and endcap toroids. The arrangement of the solenoid and the toroid magnets is shown in Figure 5.11.

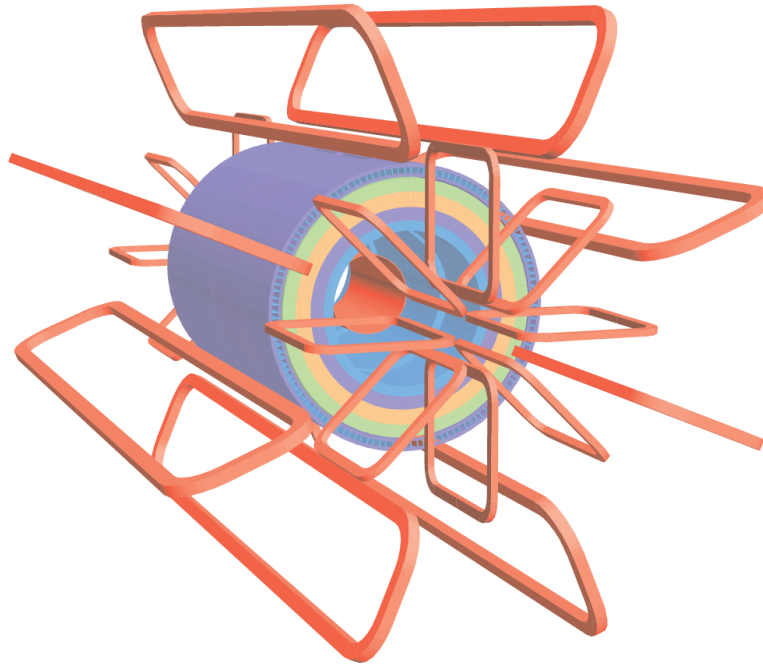


Figure 5.11: The geometric layout of the magnet system with central solenoid, tile calorimeter layers and return yoke, eight barrel toroid coils, and two sets of eight end-cap toroid coils. The magnets themselves are shown in red while the tile calorimeter structure is shown in different colors representing the different magnetic properties of the different layers and outer yoke structure.

The solenoid is aligned on the beam axis and provides a 2 T axial magnetic field for the inner detector while minimizing the radiative thickness in front of the barrel electromagnetic calorimeter. Therefore, the solenoid assembly contributes a total of 0.66 radiation lengths at normal incidence. The solenoid inner and outer dimensions are 2.46 m and 2.56 m, respectively. The solenoid is constructed with a single-layer coil wound with an Al-stabilized NbTi conductor inside a 12 mm thick

aluminum support cylinder.

The barrel and endcap toroids produce fields of strength 0.5 T and 1 T, respectively. The barrel toroid consists of eight coils encased in individual racetrack-shaped, stainless-steel vacuum vessels. The barrel toroid system is 25.3 m in length, with inner and outer diameters of 9.4 m and 20.1 m, respectively. Each endcap toroid consists of a single cold mass built from eight flat, square coil units and eight keystone wedges. Each endcap toroid is 5.0 m in length, with inner and outer diameters of 1.65 m and 10.7 m, respectively. Both the barrel and endcap toroids use the same conductor and coil-winding technology—a pure Al-stabilized Nb/Ti/Cu conductor wound into pancake-shaped coils.

5.6 Forward Detectors

Besides the main ATLAS detectors described in the previous sections, three additional detectors are installed in the very forward region. Two of these detectors determine the luminosity delivered to ATLAS. The third detector is used to measure the centrality of heavy-ion collisions.

The LUMinosity measurement using Cerenkov Integrating Detector (LUCID) [109] consists of twenty aluminum tubes located ± 17 m from the interaction point. LUCID detects inelastic pp scattering and is the primary relative-luminosity monitor in the TDAQ online infrastructure. LUCID is based on the principle that the number of interactions in a bunch crossing is proportional to the number of particles detected.

Absolute Luminosity For ATLAS (ALFA) [110] consists of Roman pots which contain scintillating fiber placed a few millimeters from the beam. The ALFA detector measurements are used to calibrate the LUCID detector to calculate the luminosity to a precision $< 5\%$.

The Zero-Degree Calorimeter (ZDC) [111] consists of alternating tungsten and quartz layers to detect forward neutrons in $|\eta| > 8.3$. ZDC performs a key role in heavy-ion collisions, where the production of forward (spectator) neutrons is directly correlated to the collision centrality.

5.7 Trigger and Data Acquisition

The ATLAS Trigger and Data Acquisition (TDAQ) is a sophisticated system responsible for online processing, selecting, and storing events of interest for offline analysis. Events are selected using a two-stage trigger system [112]—a hardware-based Level-1 (L1) trigger and a software-based high-level trigger (HLT). A schematic of the TDAQ system is shown in Figure 5.12

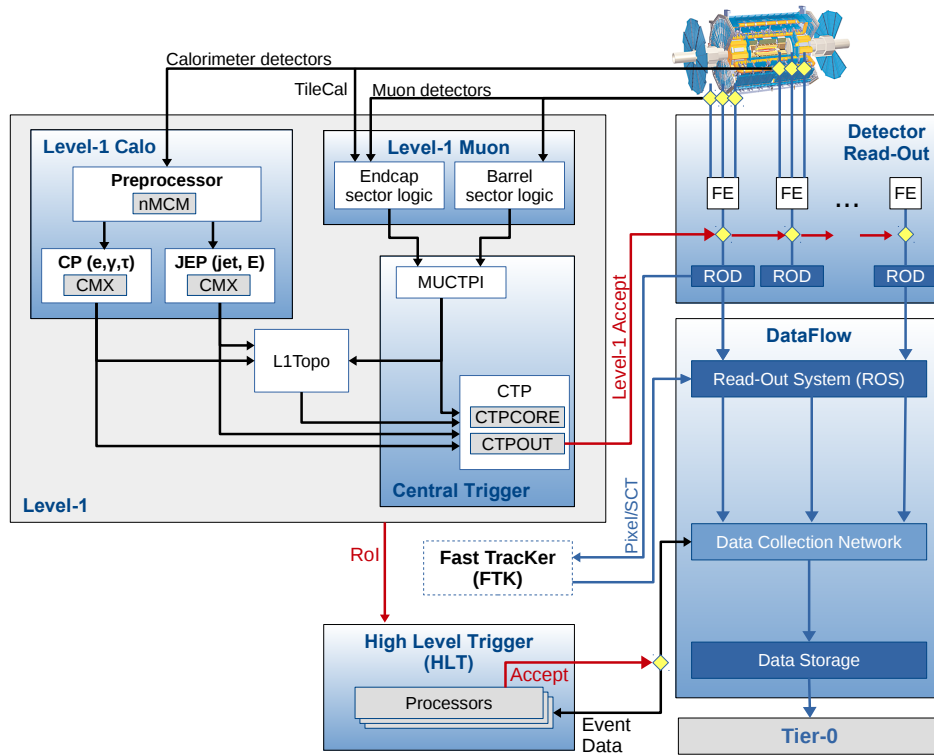


Figure 5.12: The ATLAS TDAQ system in Run 2 shows the components relevant for triggering as well as the detector read-out and data flow.

The LHC operation conditions in Run 2 are different, and harsher, with peak luminosities reaching twice the machine design limit of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A higher

peak luminosity translates to a higher pileup which poses several challenges to triggering interesting physics events and processing and storing the triggered data. Besides the increasing demands of the LHC collision environment, ATLAS sought to increase the event rates processed by various stages of the trigger system to optimize sensitivity to interesting physics signatures. Therefore, the TDAQ system underwent substantial upgrades and modifications [92] to cope with the challenging conditions expected for Run 2 data-taking.

The L1 trigger is a hardware-based system that uses custom-designed electronics to trigger on information from the calorimeter and muon detectors [113]. The Level-1 calorimeter trigger (L1Calo) is a trigger system processing signals from the electromagnetic and hadronic calorimeters in real-time to produce trigger signals to the Central Trigger Processor (CTP). Calorimeter signals are sent to the Cluster Processor (CP) and Jet/Energy-sum Processor (JEP). The CP system identifies photon, electron, and τ -lepton candidates above a threshold. The JEP identifies jet candidates and produces global sums of total and missing transverse energy. The Level-1 muon trigger (L1Muon) is based on hits from the RPCs in the barrel and the TGCs in the endcaps. L1Muon trigger estimates the candidate muon p_T with the degree of deviation from the hit pattern expected for a muon with infinite momentum [114]. The L1 trigger decision is formed by the Central Trigger Processor (CTP), which receives inputs from the L1Calo trigger, L1Muon trigger through the L1Muon Central Trigger Processor Interface (MUCTPI), and the L1 topological (L1Topo) trigger. The L1 trigger accepts events at a rate of 100 kHz down from the bunch crossing rate of about 40 MHz, within a latency of 2.5 μ sec.

For an event that is accepted by the L1 trigger, the front-end detector electronics read out the event data for all detectors. The data are sent to the ReadOut System (ROS) to buffer the data. The data from several sub-detectors are sent from the ROS to the second stage of the trigger, the HLT, upon an HLT request.

The second stage of the trigger, the HLT, is software-based and uses dedicated fast trigger algorithms to provide early rejection, followed by more precise and CPU-intensive algorithms that are similar to those used for offline reconstruction to make the final selection. The output rate of the HLT during the data-taking run is on average 1.2 kHz and an average throughput to permanent storage of 1.2 GB/sec. Once an event is accepted by the HLT, the Sub-Farm Output (SFO) sends the data

to permanent storage for offline reconstruction and exports the data to the Tier-0 facility at CERN's computing center [115].

To summarize, the ATLAS TDAQ is a two-level trigger system that uses the information from the calorimeter and muon spectrometers to provide a first-level trigger. The first-level trigger (L1) reduces the data rate from the bunch crossing frequency of 40 MHz to 100 kHz. The second-level trigger (HLT) makes use of the L1-accepted events and runs one or more feature extraction algorithms to decide whether the desired trigger condition is met or not. The second-level trigger further reduces the data rate to ~ 1.2 kHz. Events that are accepted by the HLT are then sent to Tier-0 facilities for permanent storage.

Chapter 6

Physics Object Identification and Reconstruction

We do not fear being called
meticulous, inclining as we do to
the view that only the exhaustive
can be truly interesting.

Thomas Mann
The Magic Mountain

This chapter describes the various reconstruction algorithms used to translate the data collected from the ATLAS detector subsystems into representations of final-state physics objects used for physics analysis. Events that are accepted by the L1 and HLT are reconstructed into "physics objects" such as electrons, photons, jets, etc. It should be noted that these reconstructed objects are *candidates*, and not *true particles* due to imperfections and uncertainties of the reconstruction process¹.

The signal signature of *delayed* and *displaced* photons/electrons objects is presented in this thesis. Therefore, identification and reconstruction of electron and photon objects, as well as calculation of missing transverse energy (E_T^{miss}) is vital for the realization of the final-state objects (or lack thereof, in the case of E_T^{miss}). Therefore, in this chapter, a comprehensive explanation of electromagnetic object reconstruction—from the detector signals to clustering to physics object reconstruction—is presented. This chapter also provides an overview of the calculation of E_T^{miss} , which is an important quantity used to measure the amount of energy carried by particles such as neutrinos, or those that escape detection, in the plane transverse to the pp collisions.

Section 6.1 describes the reconstruction of charged-particle tracks and identification of the primary interaction vertex. Section 6.2 describes the reconstruction of common physics objects, as well as the calculation of the missing transverse energy (E_T^{miss}).

¹E.g. reconstruction of electromagnetic objects could mis-reconstruct an electron object as a photon object and vice versa.

6.1 Track and Vertex Reconstruction

6.1.1 Primary Vertex Identification

The first step in reconstructing a collision event is the identification of the primary interaction vertex and the reconstruction of charged particle trajectories. The identification of the primary collision point, *primary vertex (PV)*, is vital to determine the *hard-scatter*² interaction.

Primary vertex reconstruction is divided into two stages—vertex finding and vertex fitting [116]. In the vertex finding stage, a set of tracks passing selection criteria listed in Table 6.1 and a seed position of the first vertex is selected. In the vertex fitting stage, the tracks and the seeds are utilized to estimate the best vertex position with an iterative fit. After the determination of the vertex position, all incompatible tracks are discarded to be used in another vertex. This procedure is then repeated with the remaining tracks in the event. The vertex with the highest $\sum p_T^2$ is defined as the primary (hard-scatter) vertex. Once the candidate PV is identified, the rest of the collision vertices are considered as *pileup*.

Parameter	Cut value
p_T	$> 500 \text{ MeV}$
$ d_0 $	$< 4 \text{ mm}$
$\sigma(d_0) [\sigma(z_0)]$	$< 5 \text{ mm} [< 10 \text{ mm}]$
Min. # SCT hits	4
Min. # Si hits	9
# holes	0

Table 6.1: Quality criteria used to select tracks for vertex finding. Si refers to the pixel or SCT detectors.

In a dense environment of the LHC, where there are multiple collisions per bunch crossing, the identification of the PV is a challenging and complex task. To illustrate the challenge of identifying the PV, consider the following event shown

²Hard-scatter interaction is the vertex where the protons collide inelastically and the resulting particles have the highest $\sum p_T^2$.

in Figure 6.1. The event display shows a candidate $Z \rightarrow \mu\mu$ physics process for a pp collision delivered by the LHC at $\sqrt{s} = 13$ TeV recorded in 2017. The tracks associated with the muon candidates shown in yellow are selected from all other tracks shown in cyan. Besides the PV there are additional 65 interaction vertices which are shown in the different colored squares.

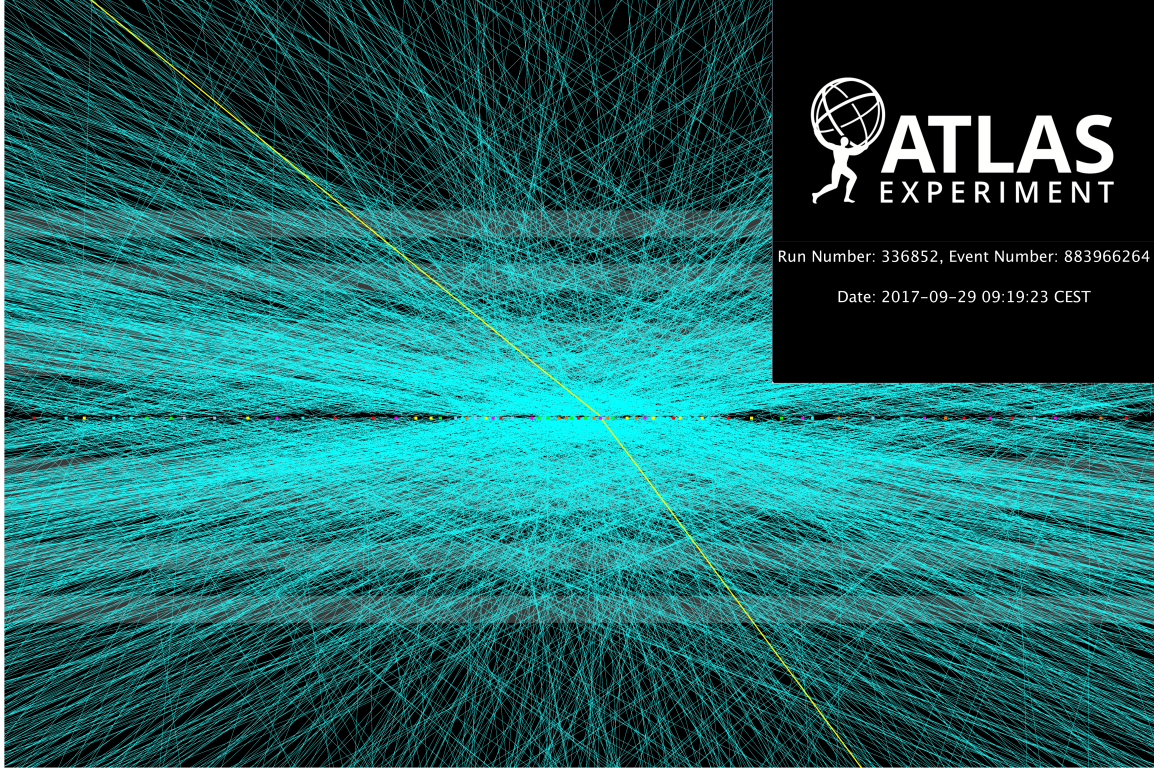


Figure 6.1: Event display of a $Z \rightarrow \mu\mu$ candidate event with 65 additional reconstructed primary vertices recorded in 2017. The candidate event tracks, shown in yellow, are selected from the rest of the tracks, shown in cyan, which are associated with pileup vertices.

6.1.2 Track Reconstruction

Charged particle trajectories are reconstructed using data from the ID. As described in Section 5.2, charged particles leave energy deposits, or *hits*, as they traverse the ID. The trajectory or *track* is reconstructed by matching the hits from various layers of the ID sub-detectors to form a continuous trajectory. However,

in a collision-dense environment, the task of reconstructing particle tracks is not simply *connecting the dots*.

Tracks are described by five parameters and a reference point, using a perigee representation (shown in Figure 6.2). The transverse and longitudinal impact parameters (d_0 and z_0) are distances of the single point of closest approach transverse to the reference point. The other three parameters are the azimuthal angle ϕ , the polar angle θ , and the ratio q/p of the charge to the momentum. Standard ATLAS track reconstruction is performed using two algorithms—*inside-out*, and *outside-in* tracking. The *inside-out* tracking uses track seeds from the pixel and the SCT detectors which are then extended to form full tracks. The *outside-in* tracking is performed in the second pass using information from the TRT and the EM calorimeter energy deposits.

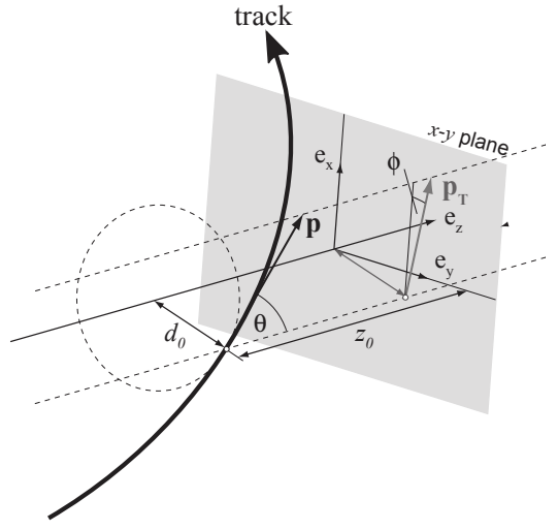


Figure 6.2: Illustration of the charged particle trajectory in a solenoidal field, along with the five track parameters (d_0 , z_0 , ϕ , θ , q/p)

Inside-out tracking

The inside-out tracking begins by forming clusters from the pixel and SCT measurements. The clusters are used to form three-dimensional measurements called *space-points* with position uncertainties determined by the detector geometry and

sensor pitch. The space-points represent the points where a charged particle traversed the active medium in the ID. For the pixel detector, each cluster corresponds to one space-point. Whereas for the SCT detector, clusters from both sides of a strip layer must be combined.

Track seeds are formed using triplets of space-points in either the pixel or the SCT detector. The seeds already provide an estimate of the momentum and impact parameters of the trajectory. The fraction of seeds that result in good-quality tracks, *purity*, varies significantly on which detector(s) recorded the space-points. Therefore, a loose selection by applying cuts on the transverse and longitudinal impact parameters is applied to improve purity. In addition, the purity is further improved by adding a *confirmation space-point* that is compatible with the particle's trajectory estimated from the seed. A combinatorial Kalman filter [117] is then used to build track candidates using the seeds and the additional space-points which are compatible with the particle's preliminary trajectory. The clustering and track-finding process result in high efficiency for reconstructing primary particles and removal of tracks created from purely random collections of space-points. However, the filtering process results in a number of track candidates where the space-points overlap or are incorrectly assigned. Therefore, an ambiguity solver resolves overlaps between track candidates and rejects incorrect combinations of unrelated clusters, *fake tracks*.

The ambiguity solver assigns each track a score based on simple measures of the track quality. Each cluster assigned to a track increases the *track score* by a weight that is proportional to the intrinsic resolution of the cluster detector. Holes³ reduce the score. The χ^2 of the track fit is also considered to penalize candidates with a poor fit. Finally, the logarithm of the track momentum is considered to prefer high-energy track.

After track scores are assigned, the ambiguity solver deals with clusters assigned to multiple track candidates. A limited number of shared hits is permitted to retain high performance in dense environments such as merged clusters shown in

³Holes are defined as intersections of the reconstructed track trajectory with a sensitive detector element that does not contain a matching cluster. These are estimated by following closely the track trajectory and comparing, within the uncertainties, the intersected sensors with the clusters on the track. Inactive sensors or regions, such as edge areas on the silicon sensors, are excluded from the hole definition.

Figure 6.3. In track candidates with shared cluster(s), the cluster(s) are assigned to the track with a higher track score, and the remaining track candidates are refit without the shared hit and scored again. Track candidates are rejected by the ambiguity solver if they fail to meet the basic quality criteria listed in Table 6.2.

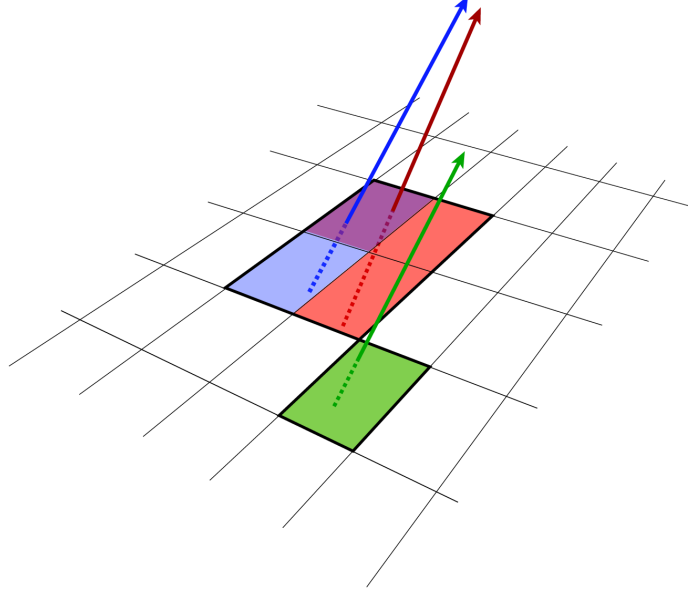


Figure 6.3: Illustration of a merged pixel cluster due to very collimated charged particles. Different colors represent energy deposits from different charged particles traversing the sensor, and the particle trajectories are shown as arrows.

For tracks that pass the ambiguity solver, an extension into the TRT detector is attempted. A Kalman filter is used to build track candidates using the TRT hits which are compatible with the track. The track candidates after adding the TRT hits are refit with the global χ^2 fitter if the extension is successful. However, Si-only tracks are kept if the fit worsens with the addition of the TRT hits. If the inclusion of the TRT hits improves the track fit, the extension is marked successful and is incorporated into the final track.

Parameter	Cut value
p_T	$> 500 \text{ MeV}$
$ \eta $	< 2.5
$ d_0^{\text{BL}} $	$< 2.0 \text{ mm}$
$ z_0^{\text{BL}} \sin \theta $	$< 3.0 \text{ mm}$
Min Si hits	7
Max. shared cluster	1 pixel or 2 SCT
Max. # holes	2 (combined pixel and SCT)
Max # pixel holes	1

Table 6.2: Quality criteria used in the ambiguity solver. Si refers to the combined pixel and SCT systems. $|d_0^{\text{BL}}|$ and $|z_0^{\text{BL}}|$ are the impact parameters calculated with respect to the beamline (BL) [3].

Outside-in tracking

The outside-in tracking algorithm is performed once the inside-out tracking is performed. The outside-in tracking is performed using *region-of-interest* (ROI) determined by energy deposits in the EM calorimeter. The algorithm starts with TRT hit segments compatible with the ROI. Once ROI-compatible TRT hit segments are found, short silicon track seeds consisting of two space-points are constructed in either the pixel and SCT detectors. The seeds are extended into track candidates using the same procedure as for the primary pass—Kalman filter, ambiguity solver, and global χ^2 fitter. The outside-in tracking can improve the acceptance of particles produced in a secondary vertex, e.g. decay of K_S^0 , or electrons originating from photon conversions.

6.2 Physics Object Reconstruction

6.2.1 Topological Clustering

Calorimeter signals of a given collision event are collected into clusters of topologically connected cells [118] in an attempt to extract the signal from the background of electronic noise and pileup. Such topological clustering is effective with the granularity of the LAr calorimeter. Finely segmented lateral read-out together with longitudinal sampling layers allows the resolution of energy-flow structures generating these spatial signal patterns over the signals induced by noise. The principle of topological clustering is to reconstruct three-dimensional "energy blobs" from particle showers in the calorimeter. Individual topological clusters, *topo-clusters*, represent the full or fractional response to a single particle, the merged response of several particles, or a combination of merged full and partial showers.

Cluster formation is controlled by the *cell signal significance*, $\zeta_{\text{cell}}^{\text{EM}}$, defined as the ratio of the cell signal to the average (expected) noise $\sigma_{\text{noise,cell}}^{\text{EM}}$ in the cell. The noise for a cell is estimated for each run year with the equation

$$\sigma_{\text{noise}}^{\text{EM}} = \sqrt{(\sigma_{\text{noise}}^{\text{electronic}})^2 + (\sigma_{\text{noise}}^{\text{pileup}})^2} \quad (6.1)$$

The cell signal significance can be expressed as

$$\zeta_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}} \quad (6.2)$$

Both the cell signal $E_{\text{cell}}^{\text{EM}}$ and $\sigma_{\text{noise,cell}}^{\text{EM}}$ are measured on the EM energy scale. Topo-clusters are formed by a growing-volume algorithm starting from a seed cell with a high significance. The seeding, growth, and boundary features of topo-clusters are controlled by the three respective parameters $\{S, N, P\}$, which are defined in terms of $\zeta_{\text{cell}}^{\text{EM}}$ and can be expressed as

$$\left| E_{\text{cell}}^{\text{EM}} \right| > S \sigma_{\text{cell}}^{\text{EM}} \implies \left| \zeta_{\text{cell}}^{\text{EM}} \right| > S \text{ (primary seed threshold)} \quad (6.3)$$

$$\left| E_{\text{cell}}^{\text{EM}} \right| > N \sigma_{\text{cell}}^{\text{EM}} \implies \left| \zeta_{\text{cell}}^{\text{EM}} \right| > N \text{ (growth threshold)} \quad (6.4)$$

$$\left| E_{\text{cell}}^{\text{EM}} \right| > P \sigma_{\text{cell}}^{\text{EM}} \implies \left| \zeta_{\text{cell}}^{\text{EM}} \right| > P \text{ (perimeter cell threshold)} \quad (6.5)$$

The default ATLAS configuration employs $S > N \geq P$ which are derived from optimizations of the response and the relative energy resolution for charged pions in test-beam experiments using ATLAS calorimeter prototypes [119]. In ATLAS reconstruction, two types of topological clustering are built—the electromagnetic 633 clusters and the combined 420 clusters. The parameters for the 633 and for the 420 clusters are listed in Table 6.3.

Parameter	EM633	Had420
Calorimeters	EM only	All
Seed signal definition	E	E
Cluster cut before splitting	$E_T > 5 \text{ GeV}$	$ E_T > 0 \text{ GeV}$
$\zeta_{\text{cell}}^{\text{EM}}$ threshold		
S	6	4
N	3	2
P	3	0

Table 6.3: Parameters used to build the two types of the topological cluster available in the standard ATLAS reconstruction.

Topo-cluster formation is a sequence of *seed* and *collect* steps, which are repeated until all topologically connected cells pass the criteria given in Equations 6.3–6.4 and their direct neighbors satisfying Equation 6.5 are found.

The clustering algorithm can be summarized as:

1. Search for the most energetic cell with $\zeta_{\text{cell}}^{\text{EM}} > S$ to form a *proto-cluster*.
2. Add all neighboring cells (and their neighboring cells) to the proto-cluster if $\zeta_{\text{cell}}^{\text{EM}} > N$.
3. Add all direct neighbors of the collected cells if $\zeta_{\text{cell}}^{\text{EM}} > P$.

An illustration of the clustering algorithm is shown in Figure 6.4. Although the above procedure is simple, there are some subtleties in the accumulation of the neighbor cells. If a particular neighbor is a seed cell, which is different from the original seed cell, the two proto-clusters are merged. If a neighboring cell is attached to two proto-clusters and its $\zeta_{\text{cell}}^{\text{EM}} > N$, the two proto-clusters are merged. The procedure is iteratively applied until the last set of neighboring cells with $\zeta_{\text{cell}}^{\text{EM}} > P$ are collected.

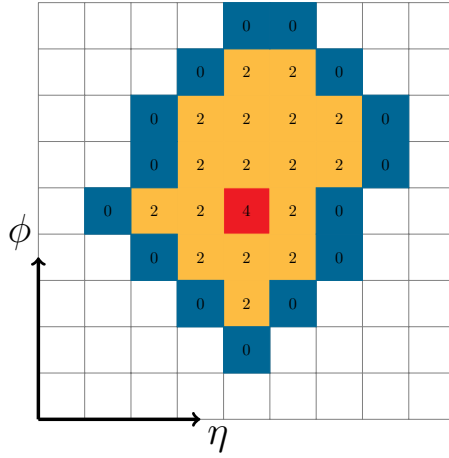


Figure 6.4: Illustration of the topo-clustering algorithm with the $\zeta_{\text{cell}}^{\text{EM}}$ assigned to each cell. The clustering selects the seed, shown in red, which forms the *proto-cluster*. The neighboring cells, shown in yellow, which are adjacent to the proto-cluster are collected into the proto-cluster. The cluster is finalized by adding perimeter cells, shown in blue, which form the boundary of the topo-cluster.

Proto-clusters could grow too large to provide a good measurement of the energy flow from the particles. Even in the case of overlapping showers, individual showers can be separated if they are far apart to form local maxima in the calorimeter.

A local maximum is defined by finding a cell whose $E_{\text{cell}}^{\text{EM}} > 500 \text{ MeV}$, called *maxima cell*. The maxima cell should also have at least four neighboring cells; none of the neighbor cells should have $E_{\text{cell}}^{\text{EM}}$ larger than the maxima cell $E_{\text{cell}}^{\text{EM}}$. The location of the cells providing local maxima are restricted to the first and second layer of the EM barrel (EMB2, EMB3, EMEC2, EMEC3), and to the first layer of the FCal (FCAL0). Each local maximum will form exactly one cluster without the possibility of merging. Parent clusters without any local maxima cells are not split.

Once the maxima cells are determined, the cluster splitting algorithm then finds cells that are neighbors to the local maxima cells. Only the cells originally clustered are used; no thresholds are applied, and no cluster merging is performed. Each neighbor cell is only shared with at most two proto-clusters.

The sharing of the signal between the two clusters with their respective energies, $E_{\text{clus},1}^{\text{EM}}$ and $E_{\text{clus},2}^{\text{EM}}$, is expressed in terms of two geometrical weights, $w_{\text{cell},1}^{\text{geo}}$ and $w_{\text{cell},2}^{\text{geo}}$, respectively. These geometrical weights are calculated from the distances of the cell to the center of gravity of the two clusters d_1 , d_2 , measured in units of a typical electromagnetic shower size scale in the ATLAS calorimeters⁴, and the cluster energies expressed by the formulae

$$w_{\text{cell},1}^{\text{geo}} = \frac{E_{\text{clus},1}^{\text{EM}}}{E_{\text{clus},1}^{\text{EM}} + r \cdot E_{\text{clus},2}^{\text{EM}}} \quad (6.6)$$

$$w_{\text{cell},2}^{\text{geo}} = 1 - w_{\text{cell},1}^{\text{geo}} \quad (6.7)$$

$$r = \exp(d_1 - d_2) \quad (6.8)$$

By construction of the weights, each cell can only appear in two proto-clusters, at most. After splitting, the final proto-clusters are used as topo-clusters used for further reconstruction of physics objects. The cluster splitting is performed to reduce biases in jet-finding and support detailed jet substructure analysis and provide a high-quality $E_{\text{T}}^{\text{miss}}$ reconstruction.

Once topo-clusters are formed, *cluster kinematic quantities* are defined using the associated cluster cells. The total cluster energy is the sum of the signal contribution

⁴This scale is motivated by the Molière radius of the electromagnetic shower, which to a good approximation is set to 5 cm.

from the associated cluster cells.

$$E_{\text{clus}}^{\text{EM}} = \sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} \quad (6.9)$$

Besides cluster energy, several topo-cluster moments which provide information about the shape of the topo-cluster and its internal signal distribution are constructed. The geometrical moments describe the direction ($\eta_{\text{clus}}, \phi_{\text{clus}}$), the location (center-of-gravity), and the size (in terms of lateral and longitudinal energy dispersion) of the cluster. The signal moments describe the cell significance ($z_{\text{cell}}^{\text{EM}}$), the signal density, timing, composition, and isolation. Most moments for a given cell variable χ_{cell} at a fixed order n are defined as

$$\langle \chi_{\text{cell}}^n \rangle = \frac{\sum_{\{i|E_{\text{cell},i}^{\text{EM}} > 0\}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} \cdot \chi_{\text{cell},i}^n}{\sum_{\{i|E_{\text{cell},i}^{\text{EM}} > 0\}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}}} \quad (6.10)$$

All moment calculations use $E_{\text{cell}}^{\text{EM}} > 0$; although higher-order moments can be reconstructed, only the centroid ($n = 1$) and the spread ($n = 2$) are used.

A summary of the topo-cluster moments are provided in Tables [6.4](#)–[6.5](#)

Parameter	Description	Definition
η_{clus}	Direction of the cluster in $(\eta - \phi)$ plane	$\eta_{\text{clus}} = \frac{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} \cdot \eta_{\text{cell},i}}{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} }$
ϕ_{clus}	Direction of the cluster in $(\eta - \phi)$ plane	$\phi_{\text{clus}} = \frac{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} \cdot \phi_{\text{cell},i}}{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}} }$

Table 6.4: Description of the geometric topo-cluster moments, ϕ_{clus} , η_{clus} .

Parameter	Description	Definition
$\sigma_{\text{noise,clus}}^{\text{EM}}$	Total noise of the topo-cluster	$\sqrt{\sum_{i=1}^{N_{\text{cell}}} (\sigma_{\text{noise,cell},i}^{\text{EM}})^2}$
$\zeta_{\text{clus}}^{\text{EM}}$	Topo-cluster significance	$\frac{E_{\text{clus}}^{\text{EM}}}{\sigma_{\text{noise,clus}}^{\text{EM}}}$
t_{clus}	Topo-cluster timing	$\frac{\sum_{\{i z_{\text{cell},i}^{\text{EM}} > 2\}} (w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}})^2 \cdot t_{\text{cell},i}}{\sum_{\{i z_{\text{cell},i}^{\text{EM}} > 2\}} (w_{\text{cell},i}^{\text{geo}} \cdot E_{\text{cell},i}^{\text{EM}})^2}$
Isolation	Topo-cluster isolation	$f_{\text{iso}} = \frac{\sum_{s \in \{\text{samplings with } E_s^{\text{EM}} > 0\}} E_s^{\text{EM}} N_{\text{cell},s}^{\text{noclus}} / N_{\text{cell},s}^{\text{neighbor}}}{\sum_{s \in \{\text{samplings with } E_s^{\text{EM}} > 0\}} E_s^{\text{EM}}}$
Average LAr quality	LAr quality factor measures the compatibility of signal pulse shape with a reference pulse shape	$\langle Q_{\text{LAr}} \rangle = \frac{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i} \cdot E_{\text{cell},i}^{\text{EM}} \cdot Q_{\text{cell},i}^{\text{LAr}}}{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i} \cdot E_{\text{cell},i}^{\text{EM}} }$
Average Tile quality	Tile quality factor measures the compatibility of signal pulse shape with a reference pulse shape	$\langle Q_{\text{Tile}} \rangle = \frac{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i} \cdot E_{\text{cell},i}^{\text{EM}} \cdot Q_{\text{cell},i}^{\text{Tile}}}{\sum_{i=1}^{N_{\text{cell}}} w_{\text{cell},i} \cdot E_{\text{cell},i}^{\text{EM}} }$
Fraction of bad LAr quality cells	Fraction of cells in LAr topocluster having bad LAr quality (i.e., $Q_{\text{LAr}} > 4000$)	$f_{\text{BadLArQ}} = \frac{N_{\text{cells}}(Q_{\text{LAr}} > 4000)}{N_{\text{cells}}^{\text{tot}}}$

Table 6.5: Description of the signal topo-moments.

6.2.2 Photons and Electrons

Electrons and photons are reconstructed using similar energy deposits in the EM calorimeter due to the similarity of their shower shapes. The presence of corresponding track(s) in the Inner Detector which is compatible with the EM shower helps distinguish electron from photon objects. A schematic illustration of the path of an electron through the ATLAS detector is shown in Figure 6.5. Despite the simple criterion of the presence of track(s) in the Inner Detector, the identification of electron and photon objects can be complicated because of the emission of bremsstrahlung photons from electron/positron particles, or conversion of photons into an electron-positron pair in the Inner Detector.

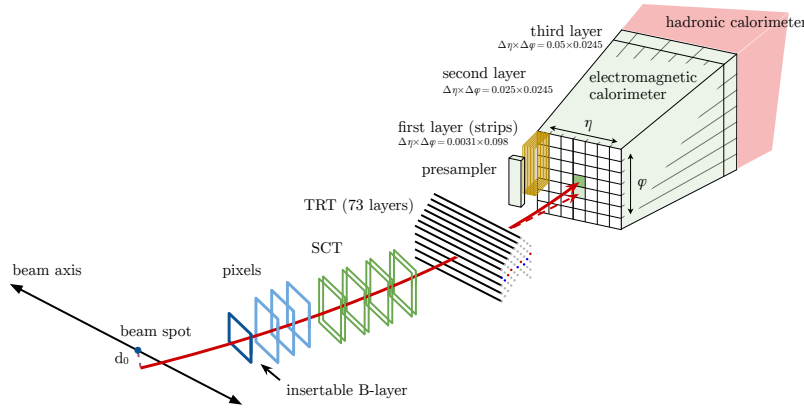


Figure 6.5: A schematic illustration of the path of an electron through the detector. The red trajectory shows the hypothetical path of an electron, which first traverses the tracking system (pixel detectors, then silicon-strip detectors, and lastly the TRT) and then enters the electromagnetic calorimeter. The dashed red trajectory indicates the path of a photon produced by the interaction of the electron with the material in the tracking system [4].

Superclustering

The reconstruction of electrons or photons begins with the formation of topoclusters using the 420-clustering described in Section 6.2.1. A sliding window algorithm with fixed-size clusters of calorimeter cells was used to reconstruct electrons and photons for the data collected by ATLAS in 2015 and 2016 [4, 118, 120]. Since 2017, the reconstruction has been improved to use dynamic, variable-size

clusters, called *superclusters* [121]. An advantage of the dynamic-size clusters is it recovers energy from bremsstrahlung photons or from electrons from photon conversions.

The supercluster reconstruction can be summarized as follows:

1. All the reconstructed EM topo-clusters are selected to be used as *seed cluster candidates*. The initial list of EM topo-clusters is sorted in order of decreasing E_T . For electrons, the seed supercluster is required to have $E_T > 1$ GeV and must be matched with at least four hits in the silicon tracking detectors. For photons, the seed supercluster is required to have $E_T > 1.5$ GeV with no requirements on track or vertex conversion matching.
2. Once a cluster meets the seed requirements, the algorithm attempts to find *satellite clusters* based on a $\Delta\eta \times \Delta\phi$ window centered on the seed barycenter. The satellite finding process is summarized in Figure 6.6. For both electrons and photons, a cluster is considered a satellite if it falls within a window of $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ since it could represent secondary EM showers originating from the same initial electron or photon. For electrons, a cluster in a window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.300$ is also added. For photons with a conversion vertex consisting of only Si hits, a cluster is added if its best-matched tracks belong to the conversion vertex matched to the seed cluster.
3. Seed clusters and the associated satellite clusters form the supercluster. The final step is to assign calorimeter cells to each supercluster. To limit the superclusters' sensitivity to pile-up noise, the size of each constituent topo-cluster is restricted to a maximal width of 0.075 or 0.125 in the η -direction in the barrel or endcap region, respectively.

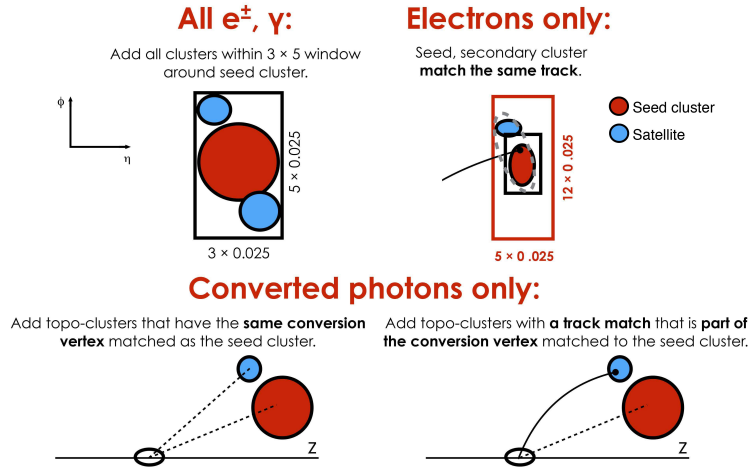


Figure 6.6: Diagram of the superclustering algorithm for electrons and photons. Seed clusters are shown in red, and satellite clusters in blue [121].

Energy calibration

Once the electron and photon superclusters are reconstructed, an energy calibration is performed. The initial energy calibration procedure is similar to the one employed in Ref. [122] with appropriate modifications made for superclusters.

A multivariate (MVA) approach is used for energy calibration, where regression Boosted Decision Trees (BDT) are trained to correct for the uncalibrated energies of the electrons and photons. A detailed explanation of the procedure is given in Ref. [122], but a brief summary of the procedure is described below:

1. An MVA regression algorithm is used to estimate the energy of the electron or photon from energy deposits in the calorimeter. The properties of the shower development are used to optimize the energy resolution and minimize the impact of material in front of the calorimeter. The MVA regression algorithm is used for this estimation and is trained on simulated events. The same algorithm is applied to data and simulation.
2. Corrections applied to data to account for the residual differences between data and simulation. These corrections account for the inter-calibration of the first two calorimeter layers, corrections to the energy shifts induced by pileup, corrections to improve the uniformity of the energy response because of inhomogeneities in the calorimeter response, and high voltage.

3. Adjustment to the overall energy scale is performed using the Z boson decays to electron-positron pairs. In addition, a correction factor to account for the difference in energy resolution between data and simulation is derived and applied to the simulation.
4. Applied corrections are verified with two independent samples— $J/\psi \rightarrow e^+e^-$ decay to probe the low-energy electrons, and $Z \rightarrow \ell\ell\gamma$ decay to probe the energy response of photons.

The invariant mass of the electron-positron pair from $Z \rightarrow ee$ events is shown in Figure 6.7. After the energy calibration is performed, the data and simulation are in good agreement.

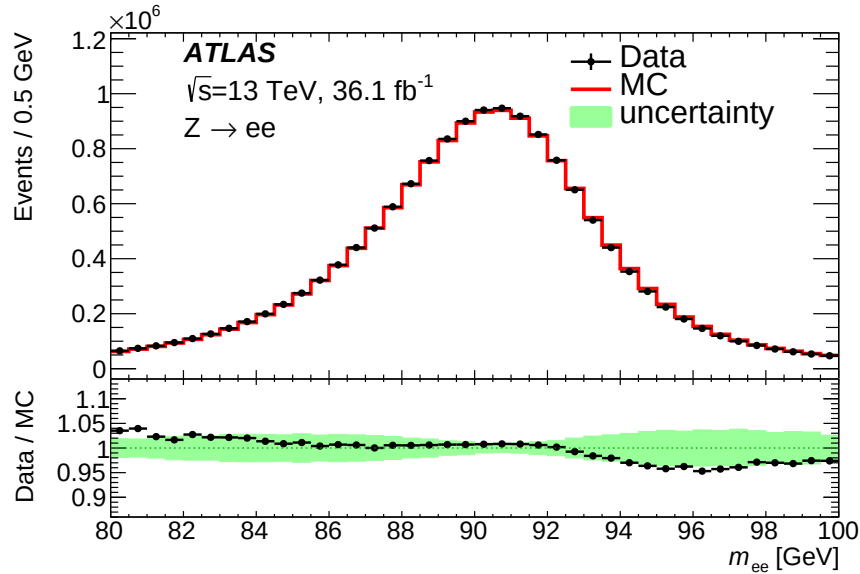


Figure 6.7: Comparison of the invariant mass distribution of the two electrons in the selected $Z \rightarrow ee$ candidates, after the calibration and resolution corrections are applied. The total number of events in the simulation is normalized to the data. The ratio is shown in the bottom plot. The uncertainty band of the bottom plot represents the impact of the uncertainties in the calibration and resolution correction factors [122].

Track Reconstruction

Electron and photon candidates are primarily distinguished by the presence of a track in the Inner Detector. The track reconstruction procedure for electrons is described in detail in Refs. [4, 120]. A brief summary of the track reconstruction, track-cluster matching, and photon conversion reconstruction is described below.

Electron and photon track reconstruction begin with EM topo-clusters that pass certain loose requirements for shower shape and energy distribution. These clusters are used to define *Regions-of-Interest (ROIs)*. Within the ROIs, the standard track pattern reconstruction [123] is performed. If the standard track reconstruction fails for a silicon track seed, a modified pattern recognition algorithm based on Kalman filter [117] formalism is used, allowing for up to 30 % energy loss at each intersection. Track candidates are then fitted with a global χ^2 fitter [124], allowing for an additional energy loss in cases where the standard fit fails. Tracks with silicon hits loosely matched to the EM clusters are refitted using a *Gaussian Sum Filter (GSF)* fitter [125].

Loosely matched, refitted tracks are then matched to EM clusters with tighter requirements in η and ϕ . In the case of multiple matched-track candidates, tracks with hits in the pixel detector are preferred, then tracks with hits in the SCT detector but not in the pixel detector. Within each category, tracks with a better matched ΔR^5 are preferred. A detailed description of the electron track-cluster matching can be found in Ref. [126].

Similar to electron track-cluster matching, loosely matched, refitted tracks are used as input for photon conversion reconstruction. Tracks with silicon hits (*Si tracks*) and tracks reconstructed only in the TRT (*TRT tracks*) are used for the photon conversion. Two-track conversion vertices are reconstructed from pairs of opposite-charge tracks which form a vertex consistent with that of a massless particle. A so-called "*single-track*" vertex, which is an individual track without hits in the innermost layers, is also reconstructed. Clusters that are matched to the converted vertex are called *converted* photons, and those which can't be matched to a conversion or a single-track vertex are called *unconverted* photons. A detailed description of the photon conversion reconstruction can be found in Ref. [120].

⁵For the ΔR matching, the extrapolation is done with the track momentum rescaled to the cluster energy first and un-rescaled second.

Identification

Electrons in the central region ($|\eta| < 2.47$) are selected using a likelihood-based (LH) identification. The inputs to the LH algorithm are listed in Figure 6.8. The electron LH makes use of signal and background *probability distribution functions* (*pdfs*) of the discriminating variables. Based on these pdfs, which are treated as uncorrelated, an overall probability is calculated for the given EM object to be either *signal* or *background*. Here, signal refers to the reconstruction of a prompt⁶ electron, and background refers to the mis-reconstruction of hadronic jets or converted photons as electrons. The signal or background likelihood constructed from the product of the signal or background pdfs is given by the formula

$$\mathcal{L}_{S(B)}(\vec{x}) = \prod_{i=1}^n P_{S(B),i}(x_i) \quad (6.11)$$

Here, $\vec{x}$ is the vector of the input variables listed in Figure 6.8, $P_{S(B),i}(x_i)$ is the value of the signal (background) pdf for variable i at value x_i . The signal and background likelihood functions are combined into a discriminant $d_{\mathcal{L}}$

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B} \quad (6.12)$$

Since the discriminant has sharp peaks at unity (zero) for signal (background), the discriminant is transformed using a sigmoid function to smooth the sharp peaks. The distribution of the transformed likelihood is shown in Figure 6.9.

⁶Prompt refers to the production of a particle in the pp collision at the PV.

Category	Description	Name	Usage
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the ranges $ \eta < 0.8$ and $ \eta > 1.37$)	R_{had_1}	e/γ
	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}	e/γ
EM third layer	Ratio of the energy in the third layer to the total energy in the EM calorimeter	f_3	e
EM second layer	Ratio of the sum of the energies of the cells contained in a $3 \times 7 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 7×7 rectangle, both centred around the most energetic cell	R_η	e/γ
	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	w_{η_2}	e/γ
	Ratio of the sum of the energies of the cells contained in a $3 \times 3 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 3×7 rectangle, both centred around the most energetic cell	R_ϕ	e/γ
EM first layer	Total lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of $\Delta\eta \approx 0.0625$ and i_{max} is the index of the highest-energy cell	$w_{s \text{ tot}}$	e/γ
	Lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of 3 cells around the highest-energy cell	$w_{s 3}$	γ
	Energy fraction outside core of three central cells, within seven cells	f_{side}	γ
	Difference between the energy of the cell associated with the second maximum, and the energy reconstructed in the cell with the smallest value found between the first and second maxima	ΔE_s	γ
	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}	e/γ
	Ratio of the energy measured in the first layer of the electromagnetic calorimeter to the total energy of the EM cluster	f_1	e/γ
Track conditions	Number of hits in the innermost pixel layer	$n_{\text{innermost}}$	e
	Number of hits in the pixel detector	n_{pixel}	e
	Total number of hits in the pixel and SCT detectors	n_{Si}	e
	Transverse impact parameter relative to the beam-line	d_0	e
	Significance of transverse impact parameter defined as the ratio of d_0 to its uncertainty	$ d_0/\sigma(d_0) $	e
	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee	$\Delta p/p$	e
	Likelihood probability based on transition radiation in the TRT	eProbabilityHT	e
Track-cluster matching	$\Delta\eta$ between the cluster position in the first layer of the EM calorimeter and the extrapolated track	$\Delta\eta_1$	e
	$\Delta\phi$ 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	$\Delta\phi_{\text{res}}$	e
	Ratio of the cluster energy to the measured track momentum	E/p	e

Figure 6.8: Discriminating variables used for electron and photon identification. The usage column indicates if the variables are used for the identification of electrons, photons, or both. For variables calculated in the first EM layer, if the cluster has more than one cell in the ϕ direction at a given η , the two cells closest in ϕ to the cluster barycenter are merged and the definitions below are given in terms of this merged cell. The sign of d_0 is conventionally chosen such that the coordinates of the perigee in the transverse plane are $(x_0, y_0) = (-d_0 \sin \phi, d_0 \cos \phi)$, where ϕ is the azimuthal angle of the track momentum at the perigee [121].

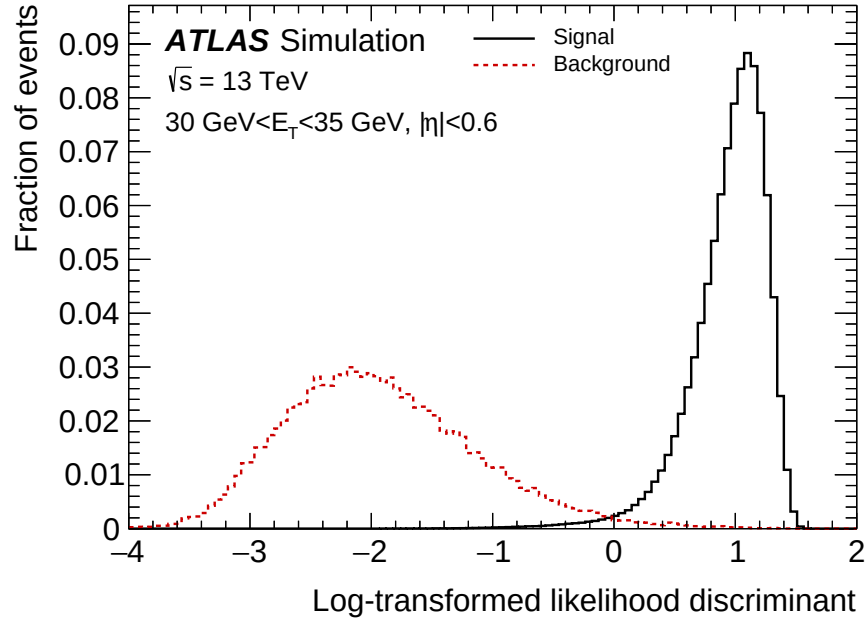


Figure 6.9: The transformed LH-based discriminant for the reconstruction of electron candidates with good quality tracks with $30 \text{ GeV} < E_T < 35 \text{ GeV}$ and $|\eta| < 0.6$. The black distribution is for prompt electrons in a $Z \rightarrow ee$ simulation sample. The red distribution is for a generic two-to-two process such as multijet, $qg \rightarrow q\gamma$, $q\bar{q} \rightarrow g\gamma$, W and Z boson production, and top-quark production.

Based on the value of the transformed discriminant, four working points are defined for electron identification. These working points referred are to VeryLoose, Loose, Medium, and Tight. These working points correspond to identifying an electron with $E_T = 40 \text{ GeV}$ with efficiencies 93%, 88%, and 80% for Loose, Medium, and Tight, respectively. The efficiencies for the different working points as a function of E_T and η are shown in Figure 6.10

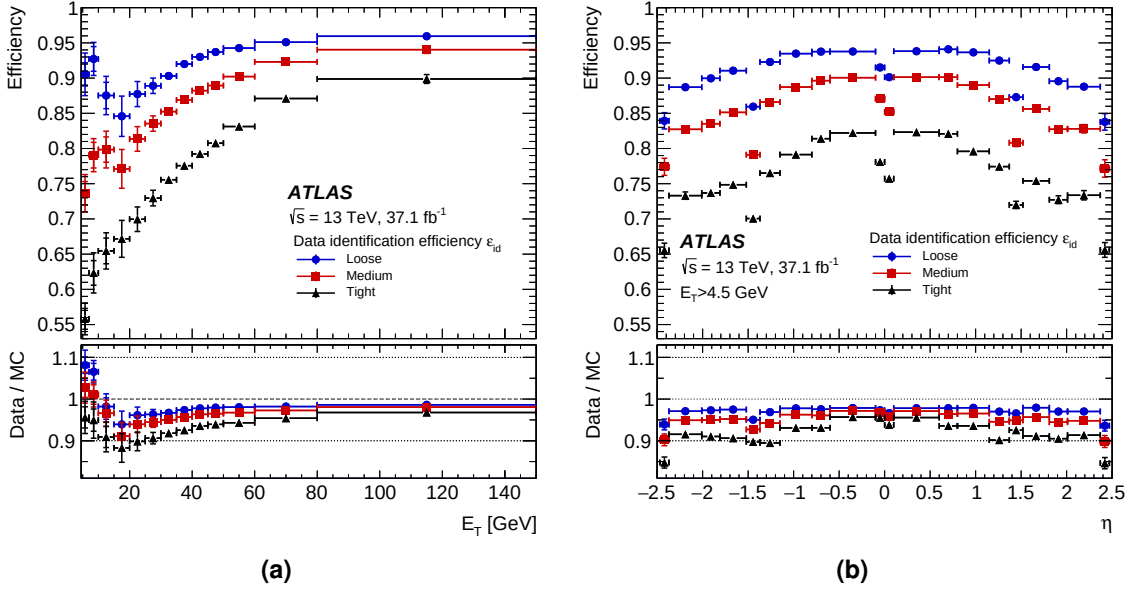


Figure 6.10: Measured LH electron-identification efficiencies in $Z \rightarrow ee$ events for the Loose (blue circle), Medium (red square), and Tight (black triangle) operating points as a function of E_T (a) and η (b). The vertical uncertainty bars (barely visible because they are small) represent the statistical (inner bars) and total (outer bars) uncertainties. The data efficiencies are obtained by applying data-to-simulation efficiency ratios that are measured in $J/\psi \rightarrow ee$ and $Z \rightarrow ee$ events to the $Z \rightarrow ee$ simulation. For both plots, the bottom panel shows the data-to-simulation ratios.

Photons are identified by applying rectangular cuts using calorimeter variables which provide a good separation between prompt photons (signal) and fake photons which arise from non-prompt photons from the decay of neutral hadrons in jets, or c-quark and light-quark jets depositing a large energy fraction in the EM calorimeter. The variables used in this *cut-based selection* are listed in Table 6.6, and are illustrated in Figure 6.11. The fine segmentation of the first layer of the EM calorimeter is particularly important in rejecting π^0 decay into two highly-collimated photons.

Category	Description	Name	Loose	Medium	Tight
Acceptance	$ \eta < 2.37$, with $1.37 \leq \eta < 1.52$ excluded	–	✓	✓	✓
Hadronic leakage	Ratio of E_T in the first sampling layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.52$)	R_{had1}	✓	✓	✓
	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}	✓	✓	✓
EM middle layer	Ratio of the energy in $3 \times 7 \eta \times \phi$ cells over the energy in 7×7 cells centered around the photon cluster position	R_η	✓	✓	✓
	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	$w_{\eta2}$	✓	✓	✓
	Ratio of the energy in $3 \times 3 \eta \times \phi$ cells over the energy of 3×7 cells centered around the photon cluster position	R_ϕ			✓
EM strip layer	Lateral shower width, $\sqrt{(\sum E_i (i - i_{max})^2)/(\sum E_i)}$, where i runs over all strips in a window of $3 \times 2 \eta \times \phi$ strips, and i_{max} is the index of the highest-energy strip calculated from three strips around the strip with maximum energy deposit	w_3			✓
	Total lateral shower width $\sqrt{(\sum E_i (i - i_{max})^2)/(\sum E_i)}$, where i runs over all strips in a window of $20 \times 2 \eta \times \phi$ strips, and i_{max} is the index of the highest-energy strip measured in the strip layer	w_{tot}			✓
	Energy outside the core of the three central strips but within seven strips divided by energy within the three central strips	F_{side}			✓
	Difference between the energy associated with the second maximum in the strip layer and the energy reconstructed in the strip with the minimum value found between the first and second maxima	ΔE			✓
	Ratio of the energy in the first layer to the total energy of the EM cluster	f_1			✓
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in the secondary maximum in the cluster to the sum of these energies	E_{ratio}		✓	✓

Table 6.6: Discriminating variables used for the Loose and Tight photon identification working points [120].

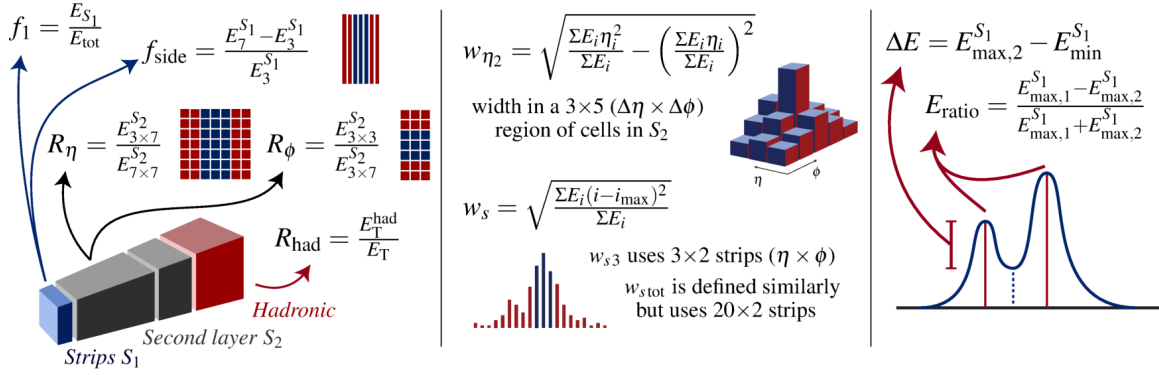


Figure 6.11: Schematic representation of the photon identification discriminating variables, from Ref. [127]. $E_C^{S_N}$ identifies the electromagnetic energy collected in the N^{th} longitudinal layer of the electromagnetic calorimeter in a cluster of properties C , identifying the number and/or properties of selected cells. E_i is the energy in the i^{th} cell, η_i the pseudorapidity centre of that cell [120].

Three working points—Tight, Medium, and Loose—are constructed based on the variables used for the cut-based selection. The Loose working point is based only on shower shapes from the second layer of the EM calorimeter, and on the energy deposited in the hadronic calorimeter [128]. The Loose working point was used to trigger on single- and di-photon events in the 2015–2016 data-taking years [121]. The Medium working point, which adds a loose cut on the E_{ratio} variable, became the main trigger in 2017 to maintain an acceptable trigger rate. The Loose and Medium identification criteria are the same for converted and unconverted photons. The Tight identification is designed to select a subset of photons passing the Medium identification. The Tight identification is optimized using TMVA and performed separately for converted and unconverted photons. A detailed description of the Tight identification is provided in Ref. [121].

In this thesis, the signal signature consists of a pair of electrons or photons produced from the decay of the $\tilde{\chi}_1^0$ to the Higgs/ Z boson. The electrons are reconstructed as “*photon objects*”, i.e., the candidate electron objects are reconstructed without tracking information from the Inner Detector. Since the decay of the $\tilde{\chi}_1^0$ is displaced with respect to the primary vertex, the tracks which would be produced by the displaced electrons would not be high-quality, and would very likely fail the track-reconstruction and track-cluster reconstruction steps outlined in this chapter. Therefore, to achieve good signal acceptance, the displaced electrons

are reconstructed using only the calorimeter information. The di-EM objects are reconstructed using the Medium photon identification criteria.

Isolation

The identification of candidate photon or electron signal objects from the background objects is a significant challenge in the dense ATLAS environment. The challenge to identify relevant physics objects becomes more difficult when the physics objects, produced with a significant Lorentz-boost, produce decay objects which are collimated, or if there is significant background activity due to the high intensity of the collisions. Variables are constructed that quantify the amount of activity in the vicinity of the candidate object, thereby providing a measure of the *isolation* of the candidate object with respect to the background objects. Isolation measurements consist of both track and calorimeter information.

Calorimeter-based isolation is performed by building an isolation variable which is a cone of size ΔR^7 centered around the electromagnetic object's EM cluster position. The energies of all positive-energy topo-clusters, whose barycenters fall within the cone of size ΔR , as shown in Figure 6.12, are summed to form the raw isolation energy variable, $E_{T,raw}^{isol}$. The raw isolation energy includes the energy deposited by the candidate electromagnetic object, called the core energy E_T^{core} . The core energy is subtracted from the raw isolation energy by removing cells included in a $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ rectangle around the candidate's direction, as illustrated in Figure 6.12. Although this simple subtraction is a stable scheme for signal and background candidates for any transverse momentum and pileup, it does not subtract the entire contribution of the core energy, and an additional leakage correction is needed. The leakage correction is parametrized as a function of E_T and $|\eta|$ using simulated events of single electrons and photons without pileup. An additional correction for the pileup and underlying-event contribution is also estimated [4].

The fully-corrected calorimeter isolation variable is computed as

$$E_T^{coneXX} = E_{T,raw}^{isolXX} - E_{T,core} - E_{T,leakage}(E_T, \eta, \Delta R) - E_{T,pileup}(\eta, \Delta R) \quad (6.13)$$

$$^7\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

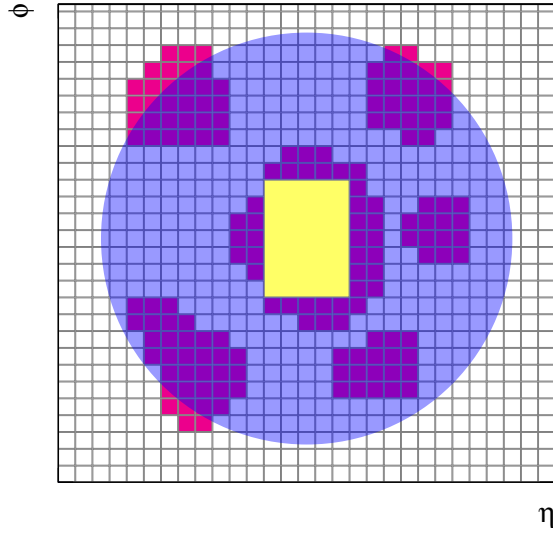


Figure 6.12: Illustration of the calorimeter isolation method. The candidate electromagnetic object is located in the center of the purple circle representing the isolation cone. All topological clusters, represented in red, for which the barycenters fall within the isolation cone are included in the computation of the isolation variable. The 5×7 cells (which cover an area of $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$) represented by the yellow rectangle correspond to the subtracted cells in the core subtraction method [4].

Here, XX denotes the size of the employed cone, $\Delta R = XX/100$. A cone of size $\Delta R = 0.2$ is used for the electron working points and cones of size $\Delta R = 0.2, 0.4$ are used for the photon working points.

Track-based isolation uses tracks with $p_T > 1$ GeV, with $|\eta| < 2.5$ and that satisfy basic track-quality requirements. A requirement on the longitudinal impact parameter, $|z_0 \sin \theta| < 3$ mm, is placed to minimize the impact of the pileup. Track-based isolation variables are constructed by summing the transverse momenta of the tracks found within a cone of radius ΔR aligned with the candidate electromagnetic object, excluding the candidate's own contribution.

The track isolation variable, $p_T^{\text{cone}XX}$, is computed by summing the transverse momentum of selected tracks within a cone centered around the electron track or the photon cluster direction, excluding the tracks matched to the candidate. Unlike calorimeter-based isolation where the minimum cone size smaller than $\Delta R = 0.2$ is difficult to build due to the finite geometry of the calorimeter, track-based isolation can have a narrower cone size due to the finer track granularity. The use of narrower and also variable-sized cones is useful to isolate objects produced in

boosted decays or dense environments. A variable-cone-size track isolation, $p_{T,\text{var}}^{\text{isol}}$ can be constructed whose size progressively decreases as a function of the p_T of the candidate

$$\Delta R = \min \left(\frac{10 \text{ GeV}}{p_T [\text{GeV}]}, R_{\text{max}} \right) \quad (6.14)$$

where, R_{max} is the maximum cone size (typically 0.2 to 0.4).

The definitions of the electron (photon) isolation working points, along with the track and calorimeter isolation selections are listed in Table 6.7 (6.8).

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 $p_T^{\text{varcone20}}$)
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 6.7: Definition of the electron isolation working points. In the Gradient working point definition, the unit of p_T is GeV. All working points use a cone size of $\Delta R = 0.2$ for calorimeter isolation and $\Delta R_{\text{max}} = 0.2$ for track isolation [4].

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

Table 6.8: Definition of the photon isolation working points [4].

Figure 6.13 shows the efficiency for the electron isolation working points as a function of E_T and η . Figure 6.14 shows the efficiency for the calorimeter-only isolation working points for unconverted and converted photons as a function of E_T in two bins of $|\eta|$.

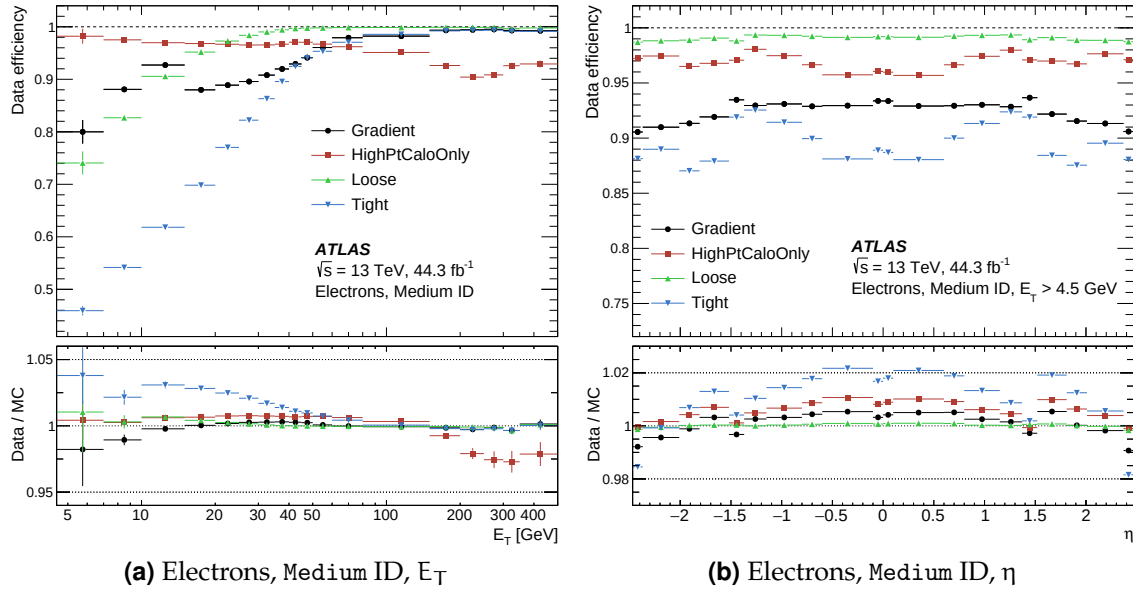


Figure 6.13: Efficiency of the different isolation working points for electrons from inclusive $Z \rightarrow ee$ events as a function of the electron E_T (a), and electron η (b). The electrons are required to fulfill the Medium selection from the likelihood-based electron identification. The lower panel shows the ratio of the efficiencies measured in data and in MC simulations. The total uncertainties are shown, including the statistical and systematic components [121].

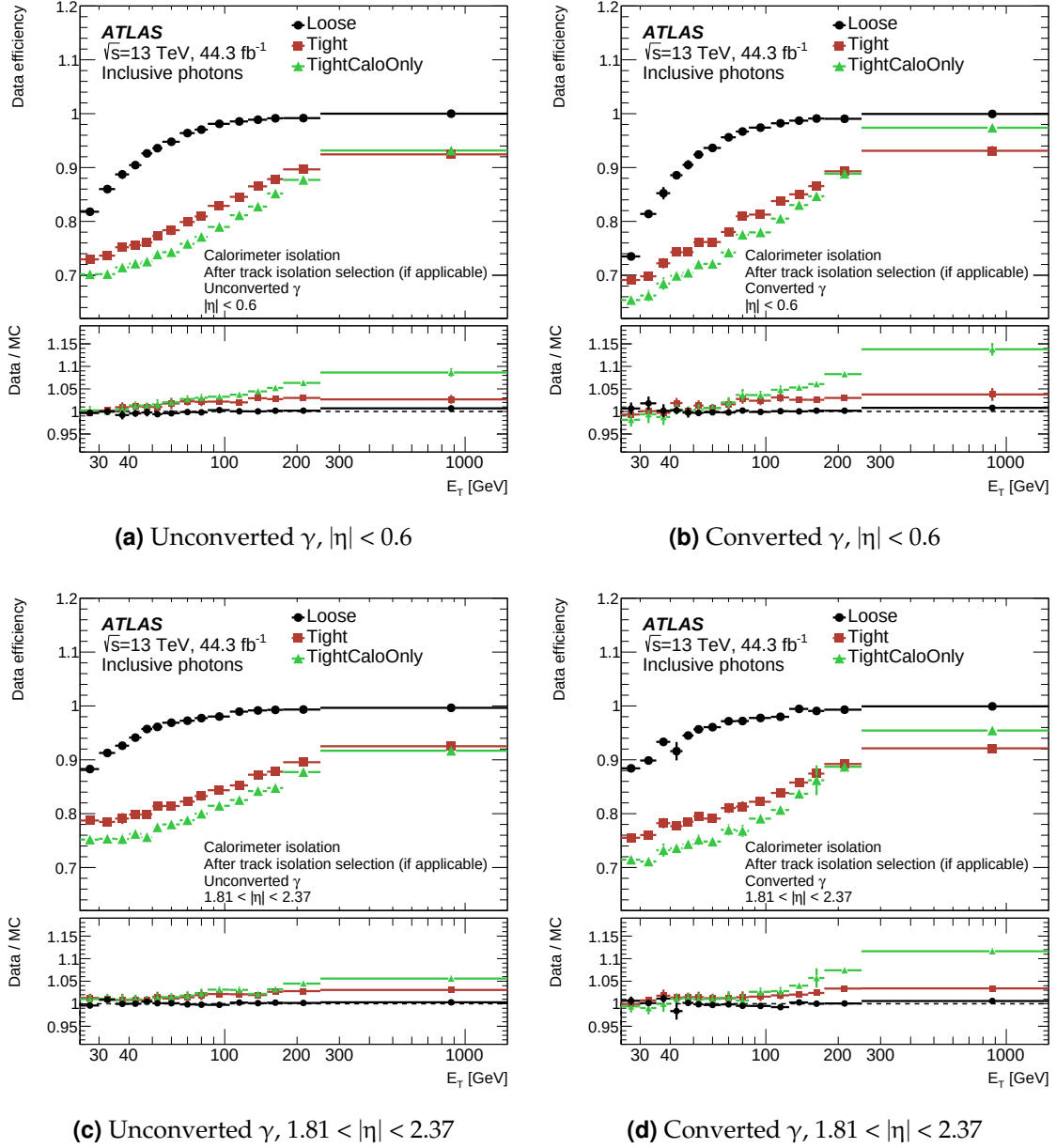


Figure 6.14: Efficiency of the different calo-only isolation working points for photons from inclusive-photon events, as a function of photon E_T in two η bins ($|\eta| < 0.6$ top, and $|\eta| > 1.81$ bottom). The results are shown for unconverted (left) and converted (right) photons. The lower panel shows the ratio of the efficiencies measured in data and in simulation. The total uncertainties are shown, including the statistical and systematic components [121].

In this thesis, the electron and photon objects are required to pass the Loose photon calorimeter-isolation working point.

6.2.3 Jets

A *jet* is a narrow cone of energy resulting from the hadronization of quarks or gluons producing a collimated hadronic shower of particles in the detector. Although jets are not used in this thesis, they are used in the calculation of E_T^{miss} and removing overlap between similarly reconstructed physics objects. Therefore, a brief description of the jet construction algorithm is provided below.

Similar to electrons and photons, jets are reconstructed from topo-clusters described in Section 6.2.1. Only positive-energy topo-clusters are used in the jet reconstruction process. A jet produced in the hard scatter vertex is expected to originate from the primary vertex. Therefore, an event-by-event correction is performed to account for the position of the primary vertex that is applied to every topo cluster. Jets that are reconstructed using only calorimeter-based information are referred to as *EMTopo* jets and were the primary jet definition used in ATLAS before Run 2.

Jet reconstruction can be improved by making use of information from the tracking and calorimeter systems. The particle flow (*PFlow*) [129] algorithm combines measurements from both the tracker and the calorimeter for jet reconstruction, thereby treating the inputs as individual particles. Energy deposited in the calorimeter by charged particles is subtracted from the observed topo-clusters and replaced by the momenta of the tracks that are matched to the topo-clusters.

Jet reconstruction is performed using the *anti- k_t* ⁸ algorithm [130]. The anti- k_t algorithm is a sequential recombination algorithm that builds clusters using the distance measures

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad (6.15)$$

$$d_{iB} = k_{ti}^{2p} \quad (6.16)$$

Where ΔR_{ij} is the distance between topo-clusters i, j in the $\eta - \phi$ plane, d_{iB} is the distance of topo-cluster i from the beamline, R is the radius of the jet, and p is

⁸Here, k_t is the transverse momentum, which is different from the notation of p_T used in this thesis.

the relative power of the energy versus geometrical scales. Note, that d_{iB} is not a physical distance, but rather is the p_T of the constituent cluster i . The parameter p describes the various types of sequential recombination algorithms— $p = 1$ is the inclusive- k_t algorithm, $p = 0$ is the *Cambridge/Aachen* algorithm, and $p = -1$ is the anti- k_t algorithm.

The recombination algorithm can be summarized as follows:

1. Calculate the distances d_{ij} between all particles and the distance d_{iB} between the particle and the beamline.
2. If $d_{ij} < d_{iB}$ then combine particles i and j . If $d_{iB} < d_{ij}$ then call particle i a jet.
3. Repeat the process until no particles remain.

The anti- k_t jet reconstruction can be understood with the following example. Consider an event with a few well-separated hard particles with momenta $k_{t1}, k_{t2}, \dots$, and several soft particles. The d_{i1} between the hard particle and the soft particle will be smaller than the distance between two soft particles. Therefore, the soft particles will cluster around a hard particle before they cluster around another soft particle. If a hard particle has no hard neighbors within a radius of $2R$, then it will accumulate all the soft particles and build a perfectly conical jet. However, if there is another hard particle such that $R < \Delta R_{12} < 2R$, then there will be two hard jets. Based on the k_t -ratio of the two hard particles, the geometry of the two jets will be different. If $k_{t1} \gg k_{t2}$, then particle 1 will be a conical jet and particle 2 will be a partly conical jet. If $k_{t1} = k_{t2}$, then neither jet will be conical. If $k_{t1} \sim k_{t2}$ then both jets will be clipped.

A key feature of this algorithm is that hard clusters are preferred which prevents the soft clusters from combining with other soft clusters. This property ensures that if there is a collinear splitting of the jet or soft emissions, the algorithm will recognize this activity belongs to the same jet. The insensitivity to soft-collinear splitting makes the algorithm *infrared and collinear safe (IRC)*.

Analogous to electron and photon energy calibration, the energy scale and resolution of the reconstructed jets are also calibrated. A detailed description of the calibration procedure can be found in Ref [131].

The identification of jets containing b hadrons (b -jets) against jets containing c hadrons (c -jets), or containing neither b nor c hadrons ($light$ -jets) is crucial for several

important physics processes. The identification of b-quarks is vital for numerous SM precision measurements, measurement of the Higgs boson properties, and also for searches beyond the SM. Several algorithms, called *b-tagging* algorithms, are used in ATLAS to identify b-jets [132]. The b-tagging algorithms exploit the long lifetime, high mass, and high decay multiplicity of b-hadrons as well as the properties of the b-quark fragmentation [133]. A detailed description of the b-jet identification can be found in Ref. [133].

6.2.4 Muons

Muon reconstruction is performed with the information from both the ID and the Muon Spectrometer (MS) systems. Muons are first reconstructed in the ID and MS independently and then combined to form muon objects [134]. In the ID, muon tracks are reconstructed with the procedure described in Section 6.1.2. MS track segments are formed by combining track segments from the MDT, RPC, and CSC subdetectors. The algorithm used to combine the subdetector segments performs a segment-seeded combinatorial search. The track segments are selected based on hit multiplicity and fit quality and are matched using their relative positions and angles. At least two matching segments are required, except in the barrel-endcap transition region where a single high-quality track can be used to build a track. A global χ^2 fit is performed using the hits associated with each track candidate. A track candidate is accepted if the χ^2 of the fit satisfies certain selection criteria. The same track segment can be initially used to build several track candidates. An overlap removal algorithm determines the best assignment to a single track or allows for the segment to be shared between two tracks.

The combined ID-MS reconstruction is performed using information from the ID, MS, and calorimeters. Four muon types are defined [134]:

1. *Combined (CB) muons*: combined track formed with a global refit that uses hits from both the ID and MS subdetectors.
2. *Segment-tagged (ST) muons*: ID track is extrapolated to the MS with at least one track segment in the MDT or the CSC. ST muons are used to reconstruct low- p_T muons or muons which fall in regions with reduced MS acceptance.

3. *Calorimeter-tagged (CT) muons*: ID track which is matched to a calorimeter energy deposit compatible with a minimum-ionizing particle. CT muons have the lowest purity but are used to recover acceptance in the region where the MS is only partially instrumented.
4. *Extrapolated (ME) muons*: Reconstructed muon trajectory based on MS tracks and a loose requirement on compatibility with originating from the IP. ME muons are used to recover acceptance in the region $2.5 < |\eta| < 2.7$ which is not covered by the ID.

Energy calibration

To describe the muon momentum scale to per mille level and the momentum resolution to the percent level, a set of corrections are applied to the muon momentum distribution obtained from simulated events. The corrections are derived using only the CB muons with their corresponding transverse momentum in the ID and the MS. The corrections are defined in $\eta - \phi$ regions and using $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events. The corrections to the simulation describe the inhomogeneity of the magnetic field, the inaccurate description of the detector dimension perpendicular to the magnetic field, and the inaccuracy in the simulation of energy of the energy loss in the calorimeter and other materials between the IP and the MS. The effect of the corrections can be seen in Figure 6.15 where the data and the corrected/uncorrected simulation are shown.

Identification

Reconstructed muons are identified by performing several quality selections to help suppress background muons, which arise from light-hadron decays, and to select signal muons with high efficiency. Several quality selections are applied to the ID and the MS tracks. For the CB tracks, the variables used are the normalized χ^2 of the combined track fit, q/p significance⁹, and ρ' ¹⁰. Four working points—Loose, Medium, Tight, and High- p_T —are defined which offer a range of purity and selection

⁹Defined as the absolute value difference between the ratio of the charge and momentum of the muons in the ID and MS divided by the sum in quadrature of the corresponding uncertainties.

¹⁰Defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track

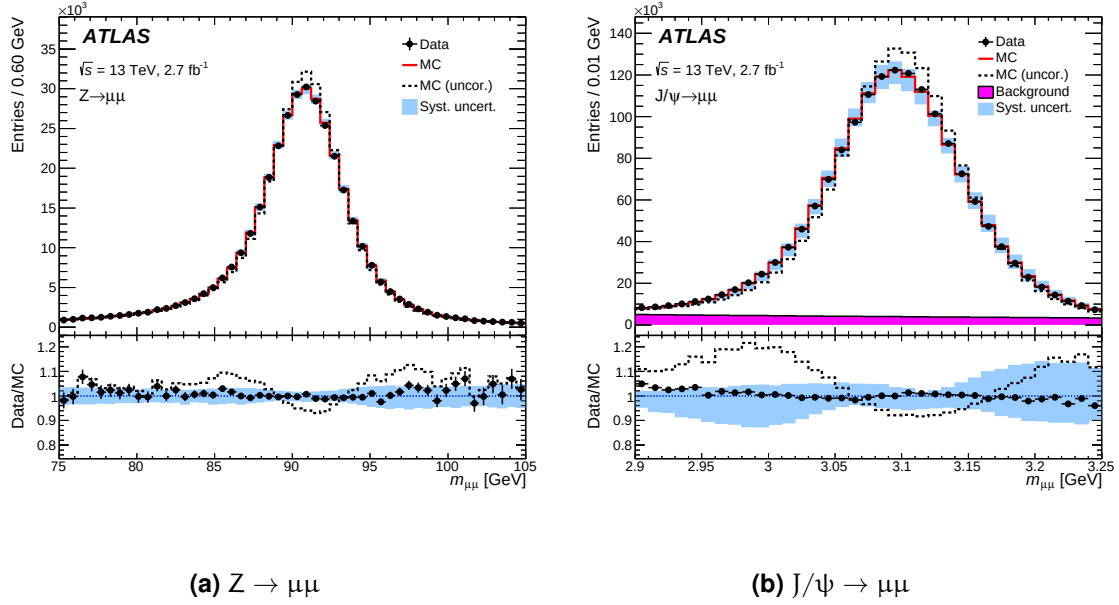


Figure 6.15: Dimuon invariant mass distribution of $Z \rightarrow \mu\mu$ (a) and $J/\psi \rightarrow \mu\mu$ (b) candidate events reconstructed with CB muons. The upper panels show the invariant mass distribution for data and for the signal simulation plus the background estimate. The points show the data. The continuous line corresponds to the simulation with the MC momentum corrections applied while the dashed lines show the simulation when no correction is applied. Background estimates are added to the signal simulation. The band represents the effect of the systematic uncertainties on the MC momentum corrections. The lower panels show the data to MC ratios. In the Z (J/ψ) sample, the MC background samples are added to the signal sample according to their expected cross sections. The sum of background and signal MC distributions is normalized to the data [134].

efficiency [134]. The ATLAS default working point is Medium which uses the CB and ME tracks and minimizes the systematic uncertainties associated with muon reconstruction and calibration.

Isolation

The isolation of signal muon candidates is performed with track-based and calorimeter-based isolation. The track-based isolation is assessed with the $p_T^{\text{varcone30}}$ variable, and the calorimeter-based isolation is assessed with the $E_T^{\text{topocone20}}$ variable [134]. Seven isolation working points—LooseTrackOnly, Loose, Tight, Gradient, GradientLoose, FixedCutTightTrackOnly, and FixedCutLoose—are defined based

on the track-based and/or the calorimeter-based discriminating variable [134].

6.2.5 Missing Transverse Energy

Missing transverse energy, E_T^{miss} , is a key quantity for event reconstruction since it provides a measure of the amount of transverse momentum carried by invisible particles produced in pp collision which escape detection. In the transverse plane momentum conservation is expected; therefore, a value of E_T^{miss} incompatible with zero not only indicates the production of SM neutrinos but may also indicate the production of new particles in theories BSM (for e.g. SUSY) which escape detection. The reconstruction of E_T^{miss} is challenging because it requires a complete description of the hard-scatter interaction using information from calorimeter and tracking systems. However, the description is obscured by detector limitations, and signal remnants from additional pp interactions occurring in the same, previous or subsequent bunch crossing, *pileup*, relative to the triggered hard-scatter interaction.

Since the incoming proton beams do not have initial momentum in the transverse plane one can write the sum of transverse momentum

$$\sum_{i \in \text{particles}} \vec{p}_T^i = \sum_{i \in \text{visible particles}} \vec{p}_T^i + \sum_{j \in \text{invisible particles}} \vec{p}_T^j = 0 \quad (6.17)$$

Thus, E_T^{miss} , which is the energy carried by invisible particles, can be represented as

$$\vec{E}_T^{\text{miss}} = \sum_{j \in \text{invisible particles}} \vec{p}_T^j = - \sum_{i \in \text{visible particles}} \vec{p}_T^i \quad (6.18)$$

Therefore, the magnitude of $\vec{E}_T^{\text{miss}}$ can be used as a proxy to observe new particles in an event by looking at all the visible particles in an event.

Since $\vec{E}_T^{\text{miss}}$ is a vector, one can define the following quantities and relations

$$\vec{E}_T^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}) \quad (6.19)$$

$$E_T^{\text{miss}} = |\vec{E}_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (6.20)$$

$$\phi^{\text{miss}} = \arctan\left(\frac{E_y^{\text{miss}}}{E_x^{\text{miss}}}\right) \quad (6.21)$$

Based on the visible particles reconstructed in ATLAS, Eq. 6.18 can be rewritten as

$$\vec{E}_T^{\text{miss}} = - \sum_{\substack{i \in \text{hard} \\ \text{objects}}} \vec{p}_T^i - \sum_{\substack{j \in \text{soft} \\ \text{objects}}} \vec{p}_T^j \quad (6.22)$$

$$\vec{E}_T^{\text{miss}} = - \underbrace{\sum_{\text{electrons}} \vec{p}_T^e - \sum_{\text{photons}} \vec{p}_T^\gamma - \sum_{\tau} \vec{p}_T^\tau - \sum_{\mu} \vec{p}_T^\mu - \sum_{\text{jets}} \vec{p}_T^j}_{\text{hard term}} - \underbrace{\sum_{\text{unused tracks}} \vec{p}_T^{\text{track}}}_{\text{soft term}} \quad (6.23)$$

Where, e, γ, μ, τ, j corresponds to electrons, photons, muons, taus, and jets, respectively. The hard term denotes the total missing transverse momentum associated with well-defined and well-calibrated objects. In contrast, the soft term denotes the p_T -sum of all particles which cannot be well-identified and not associated with the hard scatter interaction [135].

Besides the quantities listed in Eq. 6.19, the scalar sum of the transverse momenta of the objects contributing to E_T^{miss} , called $\sum E_T$, is calculated as

$$\sum E_T = \sum_{\text{electrons}} p_T^e + \sum_{\text{photons}} p_T^\gamma + \sum_{\tau} p_T^\tau + \sum_{\mu} p_T^\mu + \sum_{\text{jets}} p_T^j \quad (6.24)$$

$\sum E_T$ provides an overall scale to evaluate the *hardness* of the hard-scatter event in the transverse plane and thus provides a measure for the event activity.

E_T^{miss} hard term

Each reconstructed hard object has its own dedicated calibration procedure which translates the detector signals into fully-corrected four-momentum. A subset

of these hard objects is used in physics analysis using specific selection or isolation criteria. Therefore, the contribution from the hard term to both the E_T^{miss} and the $\sum E_T$ needs to be calculated for each physics analysis. The flexibility needed to recalculate E_T^{miss} and $\sum E_T$ is implemented using dedicated variables corresponding to specific object contributions. Additionally, in the calculation of E_T^{miss} and $\sum E_T$ the contributing objects need to be reconstructed from mutually exclusive detector signals. This rule avoids double-counting of the same signal in the E_T^{miss} and $\sum E_T$ calculation. The most commonly used order for the E_T^{miss} reconstruction sequence for the hard-object contribution starts with electrons, followed by photons, then hadronically decaying τ -leptons, and finally jets. Since muons are reconstructed from ID and MS tracks alone, there is little to no signal overlap with the other reconstructed particles in the calorimeter.

E_T^{miss} soft term

The soft term is a necessary but challenging calculation in the E_T^{miss} reconstruction. The soft term consists of all the detector signals which are not matched to the hard objects and may contain contributions from the pile-up interactions.

The calculation of the soft term has been performed using two different techniques [135]:

1. *Calorimeter-based Soft Term (CST)*: constructed from energy deposits in the calorimeter not associated with hard objects.
2. *Track-based Soft Term (TST)*: constructed from tracks not associated with any hard objects and associated with the hard-scatter vertex.

CST is sensitive to pile-up effects, whereas the TST is less sensitive to pileup effects since this method relies on the identification of the hard-scatter vertex. However, TST does not account for contributions from neutral particles and is also limited by the $|\eta| < 2.5$ pseudorapidity coverage of the ID. Figure 6.16 highlights the robustness of the TST method as a function of the number of primary vertices (N_{PV}). Since the CST is dependent on the pileup conditions, and the LHC observed an increased pileup environment in Run 2, the TST which has shown better reconstruction resolution and robustness is used as the default method for the soft term calculation.

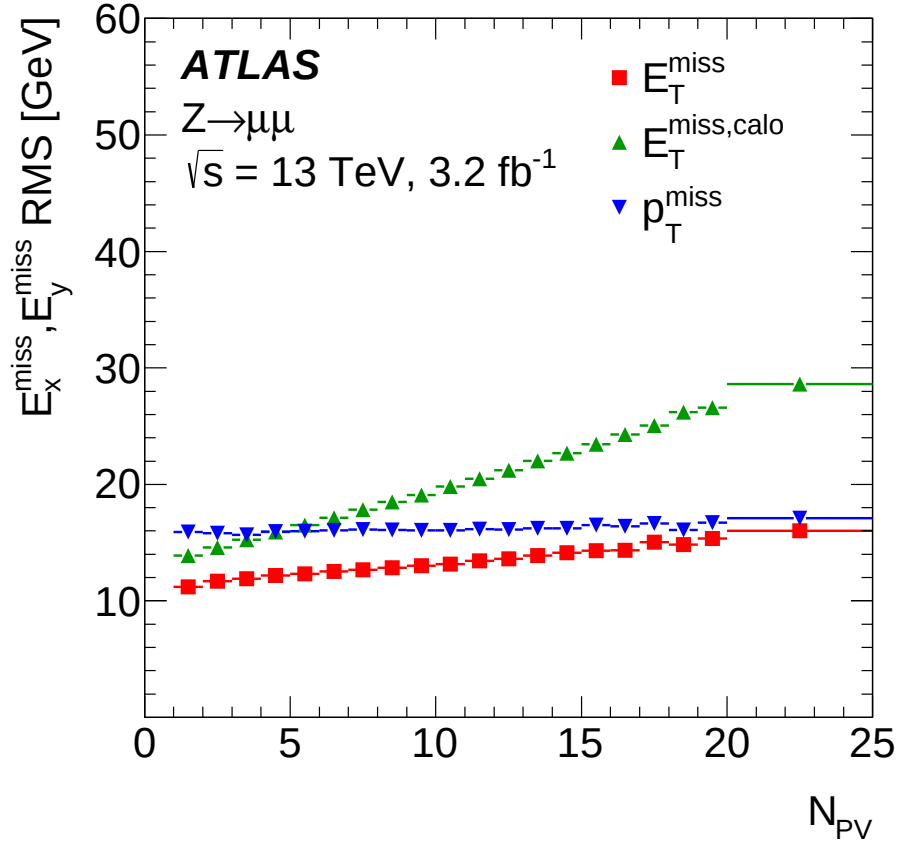


Figure 6.16: E_T^{miss} resolution for the various soft-term calculation methods. The CST method is shown in green and the TST method is shown in blue. The resolution is shown as a function of the pileup activity measured in terms of the number of primary vertices N_{PV} for an inclusive $Z \rightarrow \mu\mu$ sample. [135].

6.2.6 Overlap Removal

As discussed in the E_T^{miss} calculation, care must be taken to assign the detector signal to only one object to avoid double counting. Thus, it is necessary to implement a set of overlap removal rules. The overlap removal rules, prioritizing photon objects while maintaining standard recommendations, are listed below:

1. If an electron is overlapping with a photon, $\Delta R(e, \gamma) < 0.4$, then the electron is removed.
2. If a jet is overlapping with a photon, $\Delta R(j, \gamma) < 0.4$, or is overlapping with an electron, $\Delta R(j, e) < 0.2$, then the jet is removed.
3. Remove electrons "close to" the remaining jets ($0.2 < \Delta R(e, j) < 0.4$).
4. If a muon is overlapping with a photon or jet, $\Delta R(\mu, \gamma/j) < 0.4$, then the muon is removed.
5. If a tau lepton is overlapping with a photon, an electron, or a muon, $\Delta R(\tau, \gamma/e/\mu) < 0.4$, then the tau lepton is removed.

The final, non-duplicated physics objects are then used in the event selection described in Section 9.

Chapter 7

Data and Simulated Events

Data! data! data!... I can't make
bricks without clay.

Arthur Conan Doyle
The Adventure of the Copper Beeches

This chapter describes the ATLAS-recorded data and the simulation of the physics process of interest. The data recorded by ATLAS are carefully processed, filtered, and cleaned to ensure the available events are "good for physics". The accurate simulation of various physics processes within and beyond the SM is integral to background modeling, validation of data-analysis procedures, and for signal-search optimization. Section 7.1 describes, in brief, the data quality and basic event selections for the ATLAS data. Section 7.2 describes, in brief, the Monte Carlo simulation method and outlines the generated signal grid for the GMSB model studied in this thesis.

7.1 Data

The thesis makes use of the full ATLAS Run 2 dataset of pp collisions with the center-of-mass energy, $\sqrt{s} = 13$ TeV. During Run 2, the LHC-delivered data correspond to an integrated luminosity of 156 fb^{-1} , of which ATLAS-recorded data correspond to 147 fb^{-1} . The slight inefficiency in the data recorded by ATLAS is due to the inefficiency of the TDAQ system, and the inefficiency due to the warm-start of the tracking detectors. The events recorded by ATLAS must pass a series of data quality checks — to reject corrupted or incomplete events — which are described below. After the data quality checks, the data which are considered "good for physics" correspond to an integrated luminosity of 139 fb^{-1} .

7.1.1 Event Preselection

The events recorded by ATLAS are required to pass the following requirements:

1. Good Run List (GRL): A set of XML [136] files that contain the list of luminosity blocks¹ that are certified for use in physics analyses. A GRL is created by querying the DQ status of the data at any given time using the ATLAS defects database [137, 138].
2. Cleaning: During data-taking, an express reconstruction of the collected data is performed to identify potential issues with the detector subsystems. In the cleaning stage, the data collected during empty bunch crossings are used to identify noisy SCT detector strips. Similarly, data from empty bunch crossings are used to calculate the electronic noise from the calorimeter [139]. The empty bunch crossing data, along with calibration data, are used to identify noisy channels and to identify large bursts of coherent noise (mainly located in the endcaps) [139]. Events where such detector defects are flagged with possible defects to be discarded for physics analysis.
3. Primary Vertex: Events are required to have at least one primary vertex reconstructed with two or more associated tracks with $p_T > 500$ MeV.
4. Trigger: Events are required to fire the diphoton triggers listed in Section 7.1.2.

7.1.2 Trigger

The ATLAS trigger system (cf. Section 5.7) selects events of interest for further processing. To select events consistent with $H \rightarrow \gamma\gamma$ or $Z \rightarrow ee$ decay, events which fire the diphoton trigger are used². Events-of-interest are required to fire the `HLT_g35_loose_g25_loose`³ for the data collected in 2015–2016 and

¹A luminosity block is a period of time which corresponds to ~ 60 s of data-taking during which the instantaneous luminosity, detector, and trigger configuration, and data quality conditions are considered stable.

²Note, for this thesis electrons are reconstructed as photon objects. Therefore, events with the $Z \rightarrow ee$ decay are required to fire photon trigger, to keep consistency with the $H \rightarrow \gamma\gamma$ decay.

³The trigger naming convention is explained in detail in this [TWiki](#). A simple explanation of the naming convention is as follows: the HLT stands for the high-level trigger, the `gXX_photonID` stands for a photon with $p_T \geq XX$ GeV, and satisfies the `photonID` identification requirements.

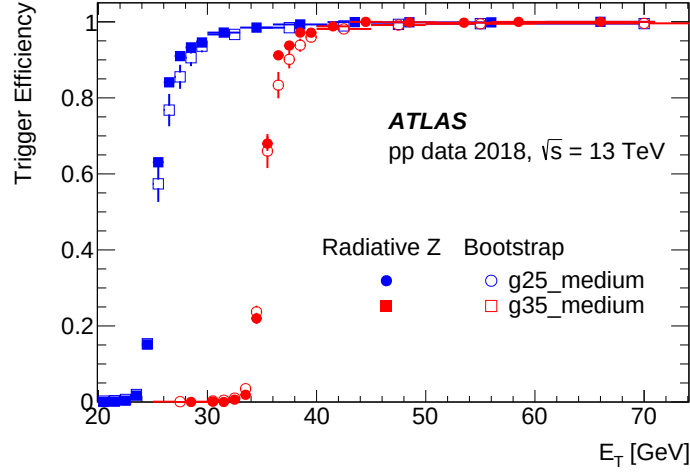


Figure 7.1: The photon trigger efficiency as a function of transverse energy (E_T) for both legs of the primary diphoton trigger in the 2018 pp data [140]. The Bootstrap method uses photons triggered by a lower level or an unbiased trigger.

HLT_g35_medium_g25_medium_L12EM20VH for the data collected in 2017–2018. Events in both data and simulation are required to fire the trigger. The efficiency of the diphoton trigger, computed using a radiative Z-boson ($Z \rightarrow \ell\ell\gamma$ decay) and a bootstrap method [140] is shown in Figure 7.1. The figure demonstrates that the triggers are not perfectly efficient at their thresholds; rather the triggers exhibit a continuous sharp rise in efficiency at their respective threshold points — a behavior called the "trigger turn-on".

7.2 Monte Carlo Simulation

Accurate prediction of signal and background processes is an important component of any BSM search. Simulations of the signal processes are necessary to optimize the analysis selections, as well as to optimize the efficiency of the selections to determine the expected number of signal events in the measurement. Monte Carlo (MC) simulation consists of several steps, from modeling of the parton distribution functions (PDFs), to the emulation of the detector to reconstruct the simulated physics objects.

The simulation of the hard scatter is the first step of MC simulation. MC event generators start by calculating the hard-scattering cross section of the physics

process at some fixed order. The matrix elements of the pp collision in a $2 \rightarrow n$ scattering are computed. The hard-scattering step relies on several parameters, most notably the renormalization factor (μ_R) and the factorization scale (μ_F) which sets the scale above which the incoming partons take part in the hard-scatter process.

The parton shower and hadronization are the next steps following the simulation of the hard-scatter. Parton showers approximate higher-order real-emission corrections to the hard scattering. The parton shower is simulated after the generation of the hard-scatter process and models the emission of both the initial- and the final-state radiation. Final-state radiation refers to emissions from an outgoing parton of the hard subprocess, and initial-state showers are those that originate from an incoming parton of the hard-scatter. The hadronization step takes the quarks and gluons produced in the hard-scatter and the parton shower and "hadronizes" them into color-neutral final states. The two most common models used for hadronization are the string [141, 142] and the cluster [143] models.

Besides simulating the hard-scatter event, the simulation of additional pp collisions must also consider incoming partons that do not participate in the hard-scatter. The soft interactions between the "spectator partons" is called the *underlying event*. The simulation must also take into account additional proton-proton interactions in each bunch crossing, i.e. the pileup. To replicate the pileup conditions in data, the generated hard-scatter events are overlaid with simulated *minimum-bias* events, which are soft inelastic collisions that are modeled to represent those observed in data. A *pileup reweighting* (PRW) is also performed to account for the actual pileup condition observed in data.

The generation of the hard-scatter event is well modeled in the Monte Carlo generators used in ATLAS. However, the generation of the low-energy QCD interactions requires the introduction of phenomenological models, due to the increase of the strong coupling constant. Processes that are affected by the phenomenological description are the multiple-parton interactions (MPI), initial- and final-state radiation, and the fragmentation processes. These models introduce an additional parameter that needs to be *tuned* from pp collision data to provide an accurate prediction.

The final step in the simulation is to run the simulated event through a detailed GEANT4 [144] simulation of the ATLAS detector to simulate the detector response.

The result of this simulation is detector signals which are treated and reconstructed in the same way as the data collected by the detector with actual pp collisions.

7.3 Simulated Signal Samples

Chapter 3.6 introduced the GMSB model studied in this thesis, along with the Feynman diagrams for the signal processes shown in Figure 3.4. Signal matrix elements are generated at leading order (LO) using MADGRAPH 2.7.3 [145] with showering and hadronization performed by PYTHIA 8 [146]. The A14 [147] tune and the NNPDF2.3LO [148] are the PDF sets used in the event generation. This section describes the choice of fixed and variable parameters employed to generate the simulated signal samples.

The signal model consists of pair-produced electroweakinos that decay into a long-lived neutralino NLSP, $\tilde{\chi}_1^0$, which subsequently decays into a Higgs/Z boson plus a gravitino, $\tilde{G}$. Of the two $\tilde{\chi}_1^0$ produced, we force the decay mode of one $\tilde{\chi}_1^0$ to be either $H + \tilde{G}$ or $Z + \tilde{G}$ with the subsequent decay of $H \rightarrow \gamma\gamma$ and $Z \rightarrow ee$. However, the other $\tilde{\chi}_1^0$ can decay to either a Higgs or Z boson which subsequently decays via SM decay modes. Thus, the final state signature consists of either two Higgs/Z bosons or a Higgs and a Z boson. For the sake of brevity, the four possible final states are named by the possible decay modes which either of the two Higgs/Z bosons can undergo. The boson which has a forced decay is named Hyy/Zee. Similarly, the boson which decays via SM modes is named HSM/ZSM. The four final states are thus called HyyHSM, ZeeZSM, HyyZSM, and ZeeHSM.

The generated signal grid scans over the $\tilde{\chi}_1^0$ mass, lifetime, and the branching ratio ($\mathcal{B}$) of the $\tilde{\chi}_1^0$ which decays into the $H + \tilde{G}$ or $Z + \tilde{G}$. Table 7.1 summarizes the signal grid. The generated signals are parameterized by the mass of the NLSP, which ranges from 100 GeV to 925 GeV, and its lifetime. For each NLSP mass value, at least two different NLSP lifetimes, typically 2 ns and 10 ns, were simulated. Since the distribution of particle decay follows an exponential decay curve, it is possible to reweight the shape of that curve and thus generalize to other lifetime values. Each event is assigned a weight according to a source signal lifetime, target signal lifetime, and the decay of the event in question. Weights for target lifetimes between 0.25 ns and 1000 ns are calculated using the generated signal point with

$\tilde{\chi}_1^0$ Mass [GeV]	Cross Section [fb]	Generated Lifetimes [ns]	
		$H \rightarrow \gamma\gamma$	$Z \rightarrow ee$
100	$16,797 \pm 603$	-	2, 10, 20
135	5996 ± 241	2, 10, 20, 50	2, 10, 20, 50
175	2268 ± 100	2, 10, 20	2, 10, 20
225	861 ± 43	2, 10, 20, 50	2, 10, 20
275	400 ± 22	2, 10, 20	-
325	207 ± 13	2, 10, 20	2, 10, 20, 50
375	116 ± 7	2, 10	-
425	68.7 ± 5.0	2, 10	2, 10, 20
475	42.5 ± 3.3	2, 10	-
525	27.2 ± 2.2	2, 10	2, 10, 20, 50
625	12.1 ± 1.1	-	2, 10, 20
725	5.78 ± 0.58	-	2, 10
825	2.93 ± 0.32	-	2, 10
925	1.55 ± 0.18	-	2, 10

Table 7.1: Signal grid of the long-lived $\tilde{\chi}_1^0$ signal models, including the $\tilde{\chi}_1^0$ masses and the lifetimes. At least one Higgs (Z boson) must decay into photons (electrons) with $\mathcal{B}(H \rightarrow \gamma\gamma) = 2.27 \times 10^{-3}$ ($\mathcal{B}(Z \rightarrow ee) = 3.36 \times 10^{-2}$).

the closest lifetime as the source distribution.

Chapter 8

Calorimeter Timing and Vertexing

The thing that is important is the
thing that is not seen.

Antoine de Saint-Exupéry
The Little Prince

This chapter describes the calibration procedure, applied offline, to the timing information obtained from the LAr calorimeter signals. The chapter also describes a novel algorithm to reconstruct a production vertex using only the calorimeter information. The calibrated timing information, along with the information from the trackless calo-vertexing algorithm form key discriminants for signal-to-background events.

The offline timing calibration optimizes the timing performance of the signals recorded by the LAr calorimeter. The calibration procedure results in a timing resolution in the range of $\sim 190\text{--}240$ ps for various signal gains and for EMB and EMEC calorimeter signals. A sub-nanosecond timing resolution enhances the search for displaced photons/electrons expected from the GMSB model studied in this thesis. Section 8.1 provides a summary of the calibration procedure. A detailed summary can be found in Refs. [149–151].

The vertex-reconstruction algorithm does not use information from the tracking system, hence a *trackless calo-vertexing* algorithm. This algorithm provides a good localization of the displaced production vertex of the signal photons/electrons. The trackless calo-vertexing procedure is described in Section 8.2.

8.1 Timing Calibration

From the readout signals, the deposited energy per cell and the time of the deposition are calculated using the optimal filtering [107] method:

$$E = \sum_{i=0}^{n-1} a_i S_i \quad (8.1)$$

$$t = \frac{1}{E} \sum_{i=0}^{n-1} b_i S_i \quad (8.2)$$

where S_i for the $i = 0, 1, 2, \dots$ are the n samples of the waveform which are read out, and a_i, b_i are the weights using the optimal filtering method. Given the form of Equation 8.1, the timing resolution can be expressed as

$$\sigma(t) = \frac{p_0}{E} \oplus p_1 \quad (8.3)$$

where E is the energy measured in GeV, and the coefficients p_0 and p_1 multiply the so-called noise term and constant term, respectively. Using collision data, the channels of the LAr calorimeter are timed with a typical online resolution of ~ 1 ns for Run 2 data. Although this resolution is sufficient to determine the bunch crossing of the triggered pp collision, the timing performance can be further improved offline.

The LAr ionized signals are digitized and read out over three gains—Low, Medium, and High (cf. Section 5.3.2). Since the gains have different readout paths in terms of the electronics, the timing calibration is performed separately for each readout gain.

The timing information from the middle layer with the maximum deposited energy, $E_{\text{cell}}^{\text{maxE}}$, is used. The choice of the middle layer $E_{\text{cell}}^{\text{maxE}}$ to perform the timing calibration is motivated because most of the EM shower energy is deposited in the middle layer. Typically, ~ 15 – 40% of the entire energy deposited in the EM cluster is deposited in the middle layer with maximum energy. Thus, the middle layer cell alone contains a high proportion of the shower information of the object.

Timing calibration is performed via a series of passes to synchronize cells and to improve resolutions, using electrons from $W \rightarrow e\nu$ and $Z \rightarrow ee$ events for calibration and validation, respectively.

8.1.1 Event Selection

Timing calibration is performed on candidate electrons from $W \rightarrow e\nu$ events and validated using $Z \rightarrow ee$ events. Both samples are selected from the full Run 2 pp dataset, corresponding to an integrated luminosity of 139 fb^{-1} . Events are cleaned by applying the standard GRL requirement, as well as $LAr \text{ error}$ ¹ and object cleaning cuts. Selected events are required to have at least one PV candidate, with at least three associated tracks.

A set of basic selection cuts applied to the electron candidates are listed in Table 8.1. For the $W \rightarrow e\nu$ events, a single isolation electron is required. In addition, the missing transverse energy (E_T^{miss}) is required to be greater than 25 GeV. The transverse mass (m_T)² of the W boson should be in the range $40 \text{ GeV} < m_T^W < 140 \text{ GeV}$. For the $Z \rightarrow ee$ events, two opposite-charged pair of isolated electrons are required, with the invariant mass satisfying $68 \text{ GeV} < m_{ee} < 108 \text{ GeV}$. Figure 8.1a shows the m_T^W distribution of the events passing the $W \rightarrow e\nu$ selection requirements, and Figure 8.1b shows the dielectron mass distribution of the events passing the $Z \rightarrow ee$ selection requirements. Both the m_T^W and the m_{ee} show contributions from background events which could be jets faking as electrons. However, since the EM shower shape of a jet-faking electron would be similar to the shower shape of a real electron, an explicit background-subtraction procedure is not performed.

Parameter	Cut Value
$\sum E_T/p_T$	< 0.3
p_T	$> 20 \text{ GeV}$
$ \eta $	< 2.47 , excluding $1.37 < \eta < 1.52$
$E_{\text{cell}}^{\text{maxE}}$	$> 1.5 \text{ GeV}$
Identification	Medium

Table 8.1: Basic selection cuts for candidate electrons used in the offline timing calibration.

¹During part of the data-taking period, an electronics failure in the LAr barrel electromagnetic calorimeter created a dead region in the second and third layers, corresponding to approximately $\Delta\eta \times \Delta\phi = 1.4 \times 0.2$. Events with electrons in this region are vetoed.

² $m_T \equiv \sqrt{2E_T^e E_T^{\text{miss}} (1 - \cos(\phi^e - \phi^{\text{miss}}))}$

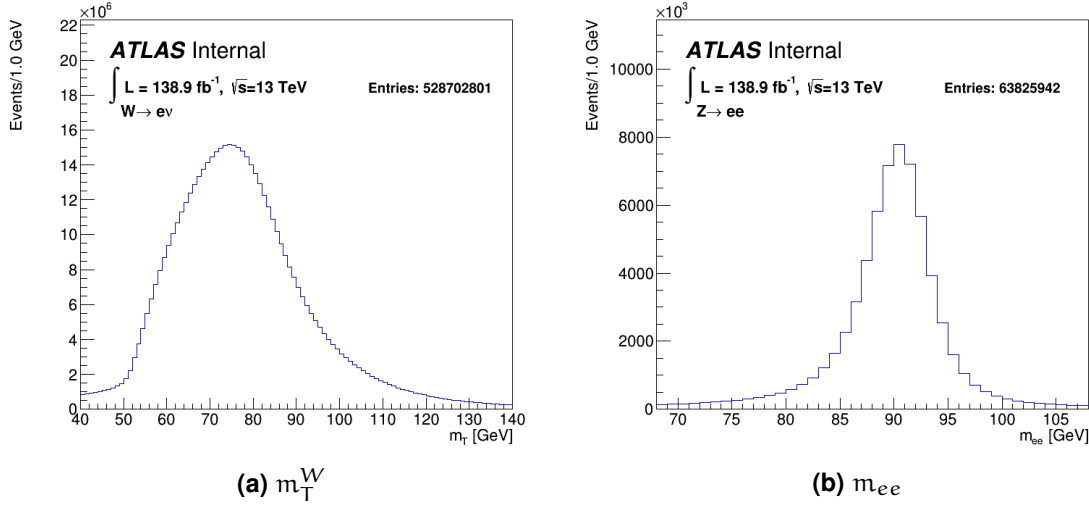


Figure 8.1: Transverse mass distribution of $W \rightarrow e\nu$ events and the dielectron mass distribution of $Z \rightarrow ee$ events

As stated earlier, the timing calibration is performed independently for the three gain scales. The calibration is also performed independently for the EMB and the EMEC calorimeters. For the Low gain (the largest signals), the statistics of events passing the selections are too low to perform a statistically robust calibration. Therefore, the calibration is performed for Medium, and High gain events. Table 8.2 summarizes the event yield for each gain, calorimeter, and the physics process.

Calorimeter	$W \rightarrow e\nu$ Sample		$Z \rightarrow ee$ Sample	
	HIGH Gain	MEDIUM Gain	HIGH Gain	MEDIUM Gain
EMB	325,360,632	15,555,104	56,340,655	3,497,677
EMEC	83,473,359	10,417,6941	16,754,845	15,131,738
Total	40,883,3991	11,973,2045	73,095,500	18,629,415

Table 8.2: Number of electron candidates in the $W \rightarrow e\nu$ and $Z \rightarrow ee$ samples, broken down according to whether they are in the EMB or EMEC calorimeter, and according to the gain used to digitize the second-layer cell used in the timing analysis.

8.1.2 Calculation of Calibration Constants

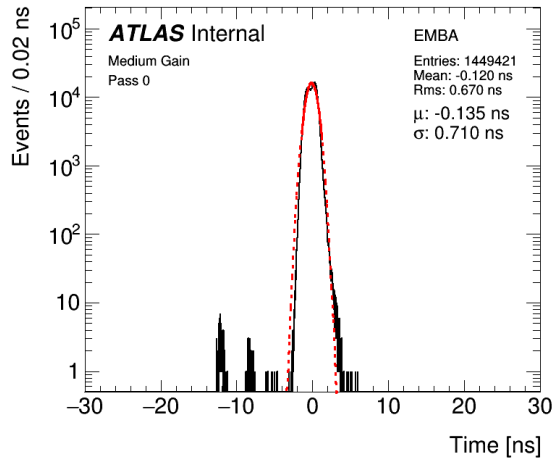
Timing calibration constants are determined using $W \rightarrow e\nu$ events. The calibration sequence is performed in several steps, where at each step the corrections are determined to bring the average reconstructed time to zero for the prompt³ events. The corrections determined at each preceding step are applied to the succeeding step.

A total of seven independent calibration passes are applied sequentially to correct averaged or fitted variations in timing. These seven calibration passes are summarized below:

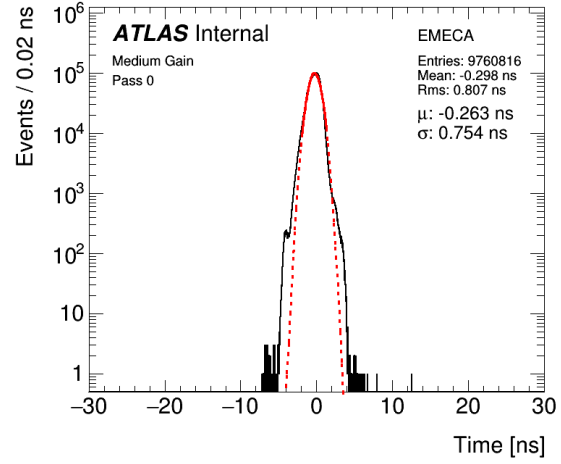
1. Pass 0: Correction to the time-of-flight (ToF) from the PV to the cell, and application of per-run correction to center the timing distributions about zero. The ToF correction is calculated analytically using the z coordinates of the PV and the calorimeter cell. Figure 8.2 shows distributions of the cell time for MEDIUM and HIGH gains, and for EMB and EMEC sub-detectors after the ToF corrections are applied. A Gaussian fit to the timing distribution is shown in red; the fit parameters are also printed on the plots. In addition to the ToF correction, one offset per run number is calculated for each sub-detector, feedthrough position, and gain.
2. Pass 1: Correction applied at a per FEB level to center the timing distribution about zero. This correction accounts for the differences in the TTC signals received at each FEB via different optical fibers.
3. Pass 2: Correction applied at a per channel level to center the timing distribution about zero. The online timing is calibrated with a resolution of ~ 1 ns. A result of this online calibration is that individual channels will have a mean time that is offset from zero by a number that is approximately randomly chosen within a range of typically ± 0.5 ns. Combining all the channels leads to a sizeable contribution to the timing resolution, of the order of $1/\sqrt{12} \approx 290$ ps. Therefore, to avoid this effect, each of the 28,672 channels is calibrated individually.

³Prompt events are defined as events which are produced in the hard-scatter and are defined to have a zero time of arrival in the calorimeter.

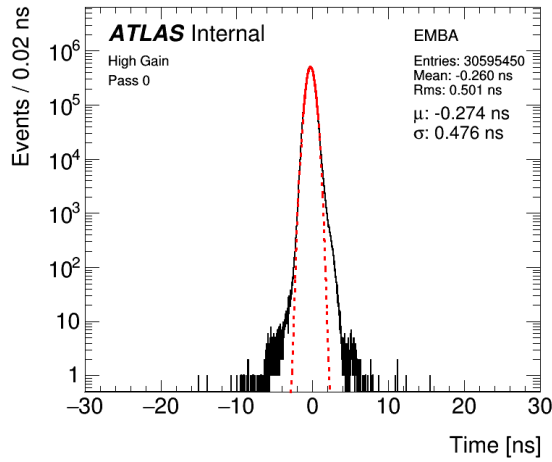
4. Pass 3: Energy-dependent correction is determined by a fit to the data in the time versus energy profile plot. Fits are performed separately for each front-end crate slot and gain. Figure 8.3 shows the profile plot of the cell energy versus time at Pass 3 (shown in black), and after the corrections are applied (shown in blue).
5. Pass 4: Corrections related to cross-talk within the middle layer are determined by fits, for each slot and gain, of time versus the cell size in units of $\delta\eta$, and $\delta\phi$. Figure 8.4 shows the profile plots of $\delta\eta$ and $\delta\phi$ before and after the corrections are applied.
6. Pass 5: Corrections related to cross-talk between the different layers determined by fits, for each slot and gain, of time versus the fraction f_1 (f_3) of the electron's energy deposited within the first (third) layer. Figure 8.5 shows the profile plots of f_1 and f_3 before and after the corrections are applied.
7. Pass 6: Individual channel offsets from Pass 2 are iterated and re-applied.



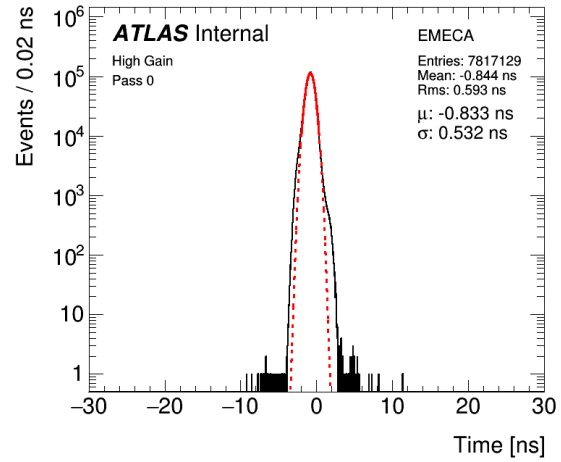
(a) EMBA, MEDIUM gain



(b) EMECA, MEDIUM gain



(c) EMBA, HIGH gain



(d) EMECA, HIGH gain

Figure 8.2: Timing distributions after Pass 0, with only the ToF correction applied. The secondary peaks and shoulders correspond to satellite collisions as well as channels with constantly shifted timing values.

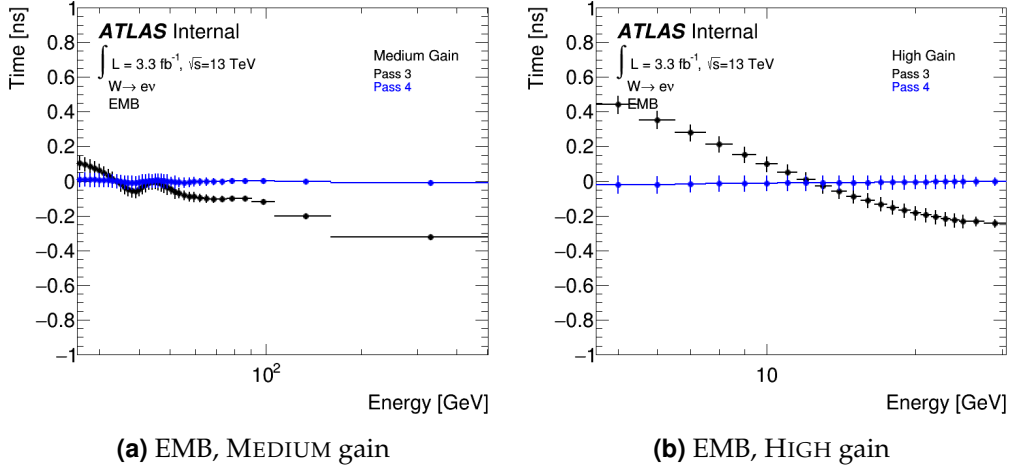
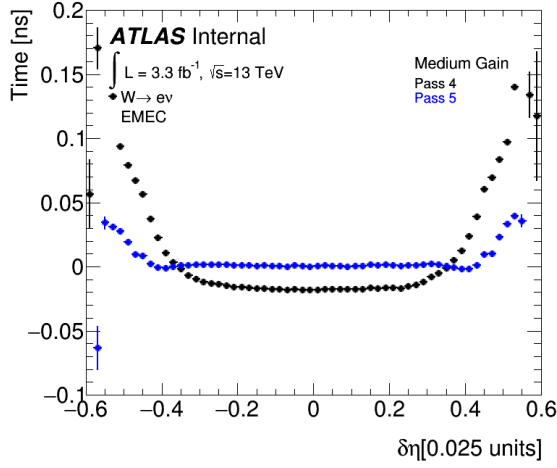
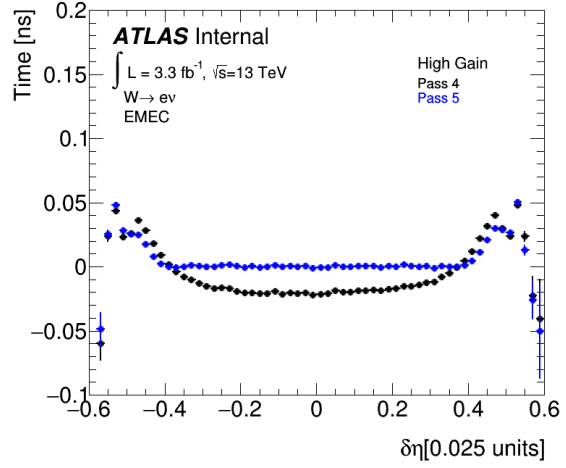


Figure 8.3: Profile plot of cell energy versus time for passes 3 and 4 after the energy-dependent correction has been applied.

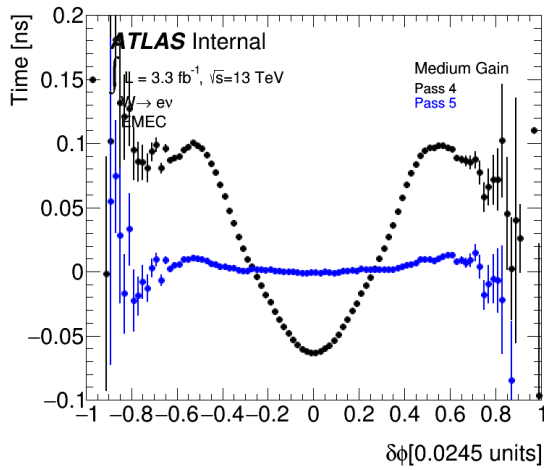
The final timing distributions for one of the N data-taking time periods are shown in Figure 8.6, for the cells on side A of EMB and for side C of the EMEC, and for both the MEDIUM and HIGH gains. Compared to Pass 0 distributions, the time distributions are now centered around zero and are significantly narrower. Figure 8.7 shows the time distributions obtained after applying corrections to the independent $Z \rightarrow ee$ validation events, for that same time period, for both EMB and EMEC and for both the MEDIUM and HIGH gains.



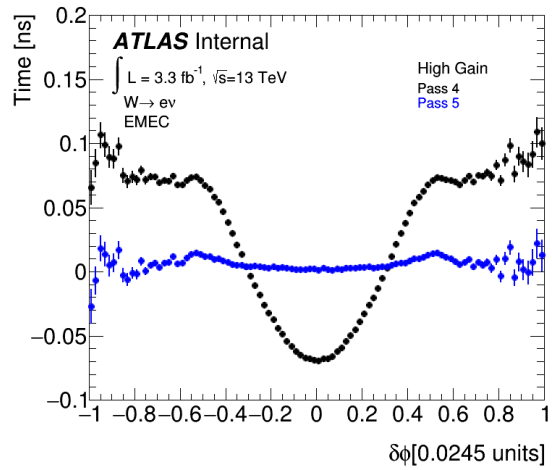
(a) $\delta\eta$, MEDIUM gain



(b) $\delta\eta$, HIGH gain

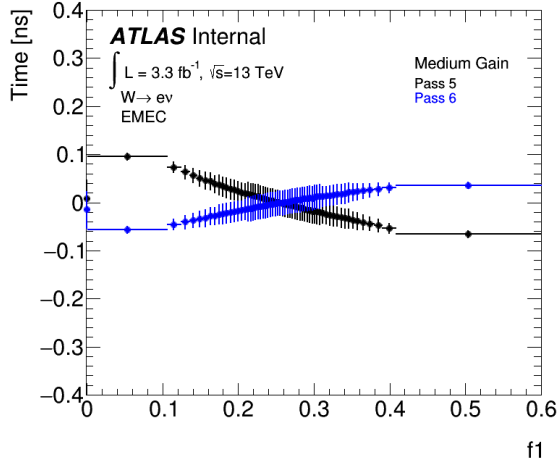


(c) $\delta\phi$, MEDIUM gain

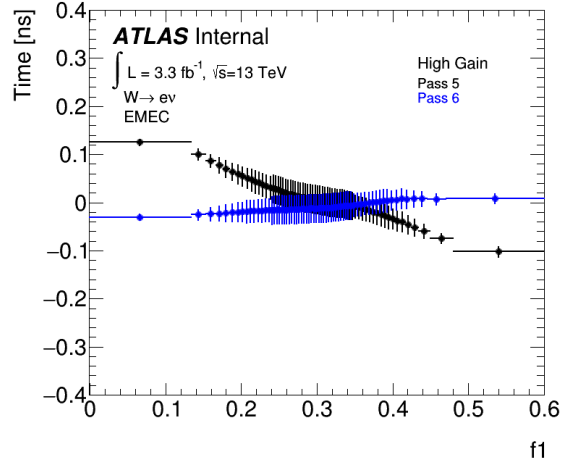


(d) $\delta\phi$, HIGH gain

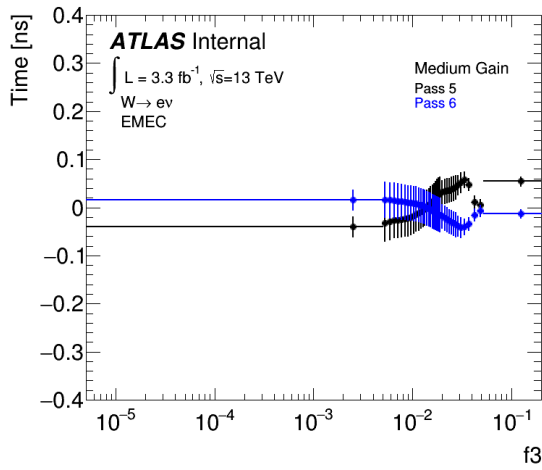
Figure 8.4: Profile plots of $\delta\eta$ and $\delta\phi$ to correct for the effect of cross-talk between the middle layer cells.



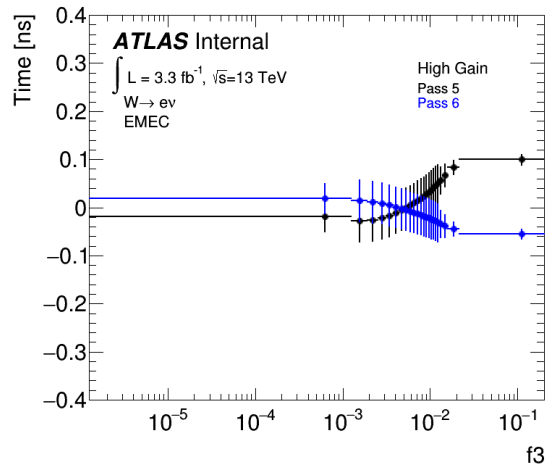
(a) f_1 , MEDIUM gain



(b) f_1 , HIGH gain

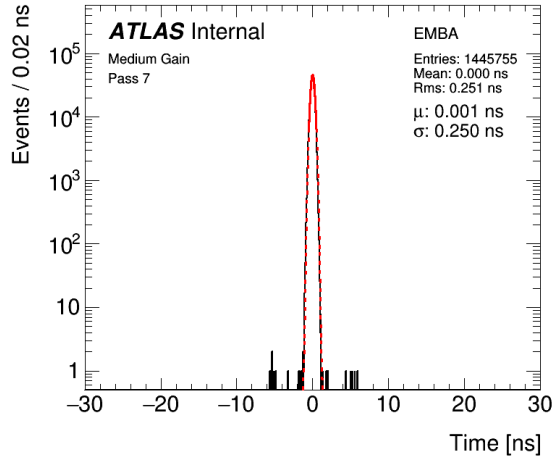


(c) f_3 , MEDIUM gain

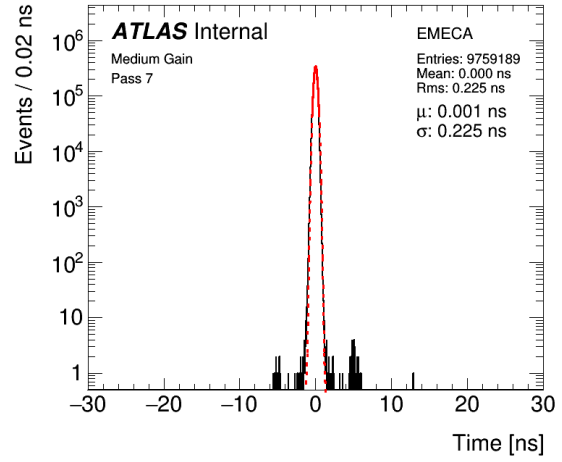


(d) f_3 , HIGH gain

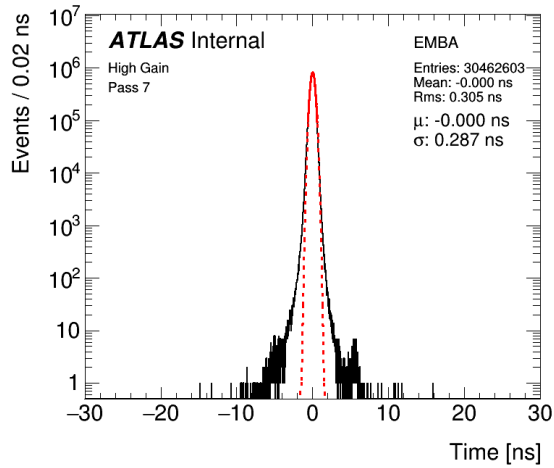
Figure 8.5: Profile plots of f_1 and f_3 to correct for the effect of cross-talk between the different layers.



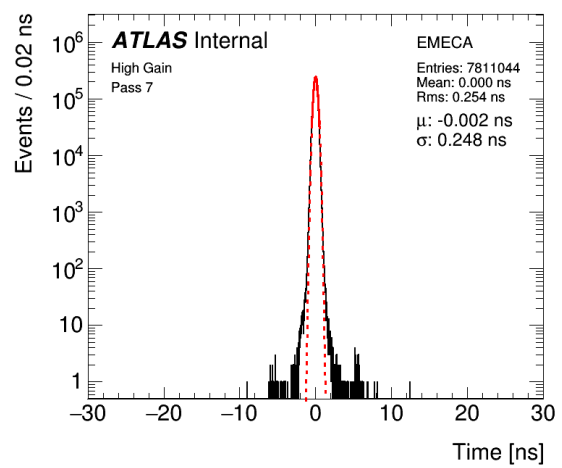
(a) EMBA, MEDIUM gain



(b) EMECA, MEDIUM gain

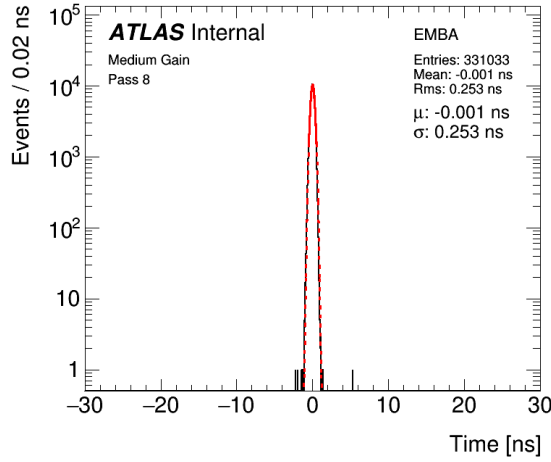


(c) EMBA, HIGH gain

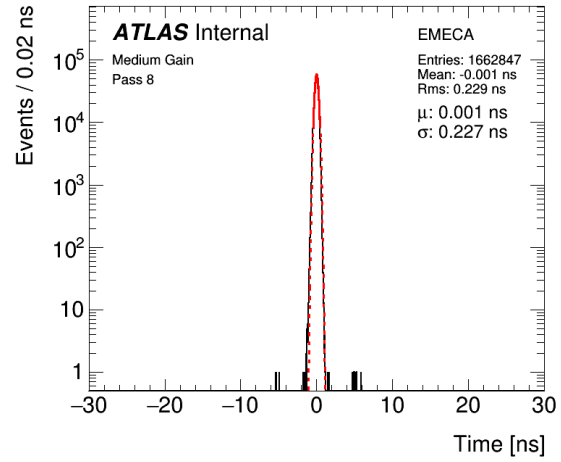


(d) EMECA, HIGH gain

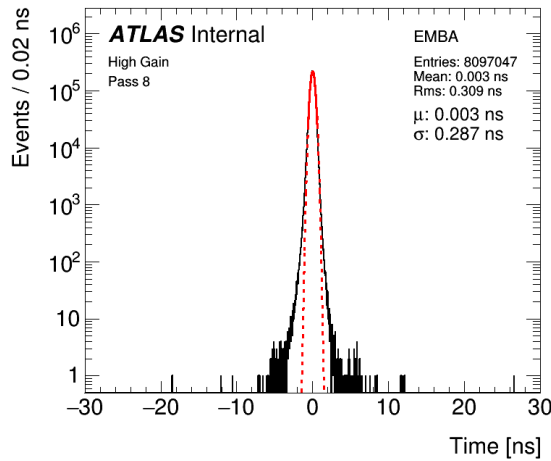
Figure 8.6: Timing distributions after Pass 7.



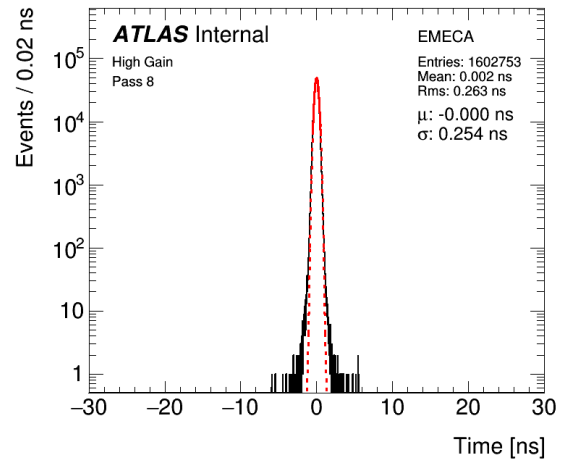
(a) EMBA, MEDIUM gain



(b) EMECA, MEDIUM gain



(c) EMBA, HIGH gain



(d) EMECA, HIGH gain

Figure 8.7: Timing distributions of the $Z \rightarrow ee$ events after application of the timing calibration corrections.

8.1.3 Timing Performance

As stated in Eq. 8.3, the timing resolution depends on the deposited energy. Figure 8.8 shows the timing resolution as a function of the deposited energy in EMB slot 11 and EMEC slot 10. The fit results, using the functional form of Eq. 8.3, are superimposed. Since the constant (noise) term depends on the gain, the fits for the timing resolution are performed separately for MEDIUM and HIGH gains. The fit results yield constant terms of 208 ps (226 ps) for the EMB (EMEC) in HIGH gain, and 217 ps (213 ps) for the EMB (EMEC) in MEDIUM gain [151]. The noise term depends on the $|\eta|$, thus, the resolution is determined in various ranges of $|\eta|$ for both the EMB and EMEC subdetectors. For the EMB, the constant term for the various $|\eta|$ regions lies in the range of ≈ 210 –240 ps for both MEDIUM and HIGH gain. For the EMEC, the constant term ranges from ≈ 210 –280 ps (≈ 190 –220 ps) for the HIGH (MEDIUM) gain [151].

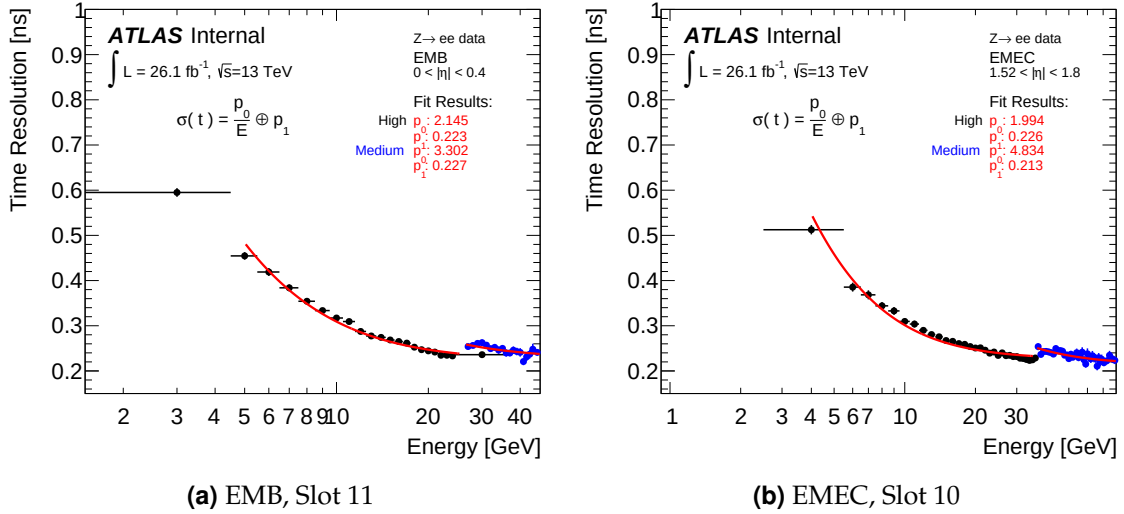


Figure 8.8: Timing resolution versus deposited energy, for MEDIUM and HIGH gains of the middle-layer cells in EMB slot 11 and EMEC slot 10.

8.1.4 Smearing in Simulation

The timing distribution from the simulation is smeared to ensure that the timing behavior of the simulation matches that of the data. The simulation does perform a simple smearing based on noise studies that generally captures the energy dependence of the resolutions. However, this simple smearing does not account for the global calorimeter effects or the correlated collision time for objects in the same event. The measured time consists of a correlated and an uncorrelated component, whose resolutions are estimated using $Z \rightarrow ee$ events in data. The correlated component, which can be seen in the core of Figure 8.9, is calculated to be ~ 190 ps. The calculation of the correlated-component resolution is consistent with the expected timing variations due to the beam spread. The uncorrelated component can be split into an energy-dependent noise term (p_0) and a constant term (p_1). Since good agreement is observed between the data and simulation timing distributions across various energies and FEB slots, the noise term is well-modeled in the simulation.

The timing smearing is performed by adding small, randomly generated fluctuations centered about zero with the correlated or the uncorrelated component resolution. The smeared time, t_{smeared} , is calculated as

$$t_{\text{smeared}} = t_{\text{raw}} + t_{\text{collision}} + t_{\text{uncorr}} \quad (8.4)$$

where, t_{raw} is the raw time produced by the simulation, $t_{\text{collision}}$ is the randomly generated collision time, and t_{uncorr} is the randomly generated uncorrelated component. The $t_{\text{collision}}$ smearing is performed per event, so each object in the event is smeared with the same value of $t_{\text{collision}}$. The t_{uncorr} smearing varies as a function of $E_{\text{cell}}^{\text{max}}$ and detector region.

8.1.5 Satellite Collisions

As discussed in Section 4.2, besides the filling of the main bunches in the LHC ring, satellite bunches, spaced ± 5 ns apart, are unintentionally filled. These satellite bunches produce the so-called satellite collisions which occur at the PV but are delayed approximately ± 5 ns with respect to the main-bunch collision. However, since the population of these satellite bunches is $\sim 10^3$ times smaller than the main bunch, the rate of collisions of satellite-satellite bunches is reduced by a

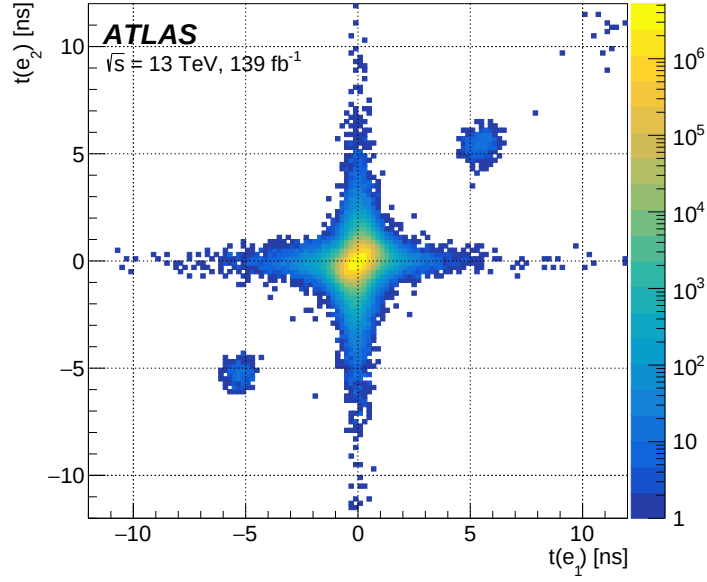


Figure 8.9: Distribution of leading versus subleading electron LAr timing values for a $Z \rightarrow ee$ analysis selection where at least two electrons are required that have $68 \text{ GeV} < m_{ee} < 108 \text{ GeV}$ and $|\Delta\eta(e_1, e_2)| > 0.1$. Populations of electrons from satellite collisions are visible at $\pm 5 \text{ ns}$ and $+10 \text{ ns}$.

factor of $\sim 10^6$. Although the satellite-satellite collisions are suppressed relative to the primary collisions, they introduce a distinct signature into the LAr timing distributions, as evident in Figure 8.9. In the two-dimensional distribution of measured electron times for a $Z \rightarrow ee$ data sample, one can clearly observe the presence of satellite collisions at $\pm 5 \text{ ns}$ and even higher multiples of 5 ns . In the figure, the presence of satellite collisions at $+10 \text{ ns}$ but the absence at -10 ns can be attributed to the asymmetry in the satellite bunch structure.

8.2 Trackless Calo-Vertexing

The fine-segmentation and the spatial resolution of the LAr calorimeter can be exploited to obtain geometrical information about the origin and direction of travel of e/γ objects. A novel method of *trackless calo-vertexing*, which determines the production vertex of a pair of di-electromagnetic (electron or photon) objects, was developed and used to obtain a localized vertex of the production of the signal photons/electrons. The position of the localized vertex provides excellent signal-to-background discrimination, where the background events are prompt or misidentified electromagnetic objects. Trackless calo-vertexing is the only way that unconverted photons can be vertexed since traditional vertexing algorithms use information from the tracking system, a technique that does not work for photons. A key ingredient of the vertexing algorithm is photon pointing, which refers to the position on the beamline with respect to the primary vertex to which the photon "points" back.

8.2.1 Photon Pointing

The LAr EM calorimeter is divided into three layers in depth, for most of its $|\eta|$ coverage. Besides providing separation between photons and π^0 meson, the fine segmentation of the EM calorimeter front-layer strips, along with the middle-layer, provides the measurement of the direction of photons⁴. The photon direction can be determined by measuring the lateral and longitudinal positions of the shower in the front- and middle-layers of the EM calorimeter, as shown in Figure 8.10. The illustration demonstrates a non-pointing photon reconstructed in the EMB calorimeter, where the angles and dimensions are exaggerated for clarity. For the photon object, a set of measurements of the barycenter positions, (R, η) , in the front- and middle-layer can be obtained. A line connecting the two barycenter positions can be constructed and extrapolated back to the beamline to determine the photon's location along the z -direction with respect to the origin (z_γ). Similarly, in the z -direction, the *distance-of-closest-approach* (DCA) (z_{DCA}) is defined as the distance from the PV.

⁴The presampler and the back-layer are not used for the pointing calculation since the cell granularity is too coarse and the energy deposition is insufficient for a reliable measurement.

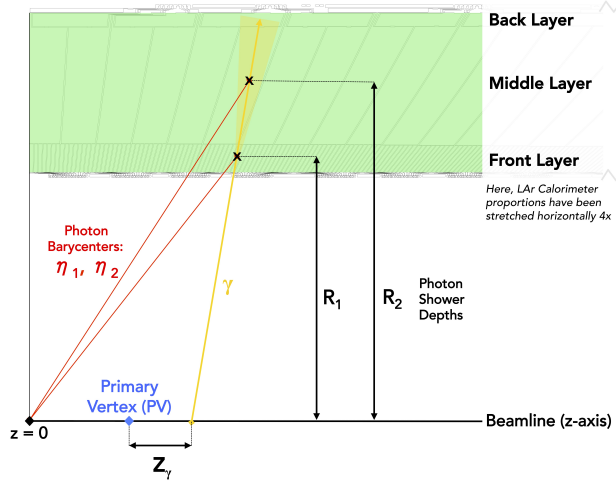


Figure 8.10: Illustration of the concept of measurement of the direction of a photon in the EM barrel calorimeter. The illustration shows the case of a non-pointing photon due to a long-lived $\tilde{\chi}_1^0$ decaying to a photon and a gravitino. The three layers of the calorimeter are represented by green boxes, while the hatching represents the projective geometry of the calorimeter. The relevant angles and distances used in the measurement of the photon direction are also shown.

The photon pointing, z_γ , is computed as

$$z_\gamma = \frac{R_1 \cdot R_2}{R_2 - R_1} (\sinh \eta_1 - \sinh \eta_2) \quad (8.5)$$

here, (R_1, η_1) and (R_2, η_2) are the cylindrical coordinates of the cluster barycenter positions in the front- and middle-layer, respectively. The computation of the η barycenter position accounts for the shower evolution across various cells, yielding a better resolution than the width of a single cell. The barycenter positions in R , also called *photon shower depths*, are parametrized as a function of the photon η and energy. Photon shower depth values are determined *a priori* using a sample of simulated prompt photons with known production vertex positions; in each LAr layer, the value of R that minimizes the η barycenter resolution is selected.

8.2.2 Pointing Resolution

Validation of the photon pointing is necessary to verify the accuracy of the detector and the shower simulation. Photon pointing is validated using $Z \rightarrow ee$ events from both data and simulation. In data, $Z \rightarrow ee$ events are produced along the beamline with a finite, non-zero spread in the z -direction due to the finite size of the pp bunches. The pointing resolution in Monte Carlo is calculated by fitting a Gaussian distribution to the quantity, $|z_{\text{origin}}|$, calculated as

$$|z_{\text{origin}}| = |z_{\text{calc}} - z_{\text{PV}}| \quad (8.6)$$

where, z_{calc} is the calculated, and z_{PV} is the primary vertex value of the photon pointing, respectively. For $Z \rightarrow ee$ data and simulated events, z_{PV} is the z -value of the primary vertex, and for the simulated GMSB signal events, z_{PV} is obtained from the secondary vertex position stored in the simulation generator-level record.

The photon pointing resolution as a function of the $|z_{\text{origin}}|$ is shown in Figure 8.11. Overlaid in the figure are the pointing resolutions for $Z \rightarrow ee$ data and simulation, which are in good agreement. Also overlaid in the figure are the pointing resolutions for several GMSB signals simulated at various values of the $\tilde{\chi}_1^0$ mass and lifetime. The pointing resolution for $Z \rightarrow ee$ events in data is also in good agreement with those of the GMSB signals. Therefore, a similar pointing performance is observed for photons and electrons, which is expected given the similarity of their EM showers. The level of agreement between data and simulation over the $|z_{\text{origin}}|$ values which can be accessed gives confidence that the photon pointing can be extrapolated using simulation over the high displacement values expected for signal events.

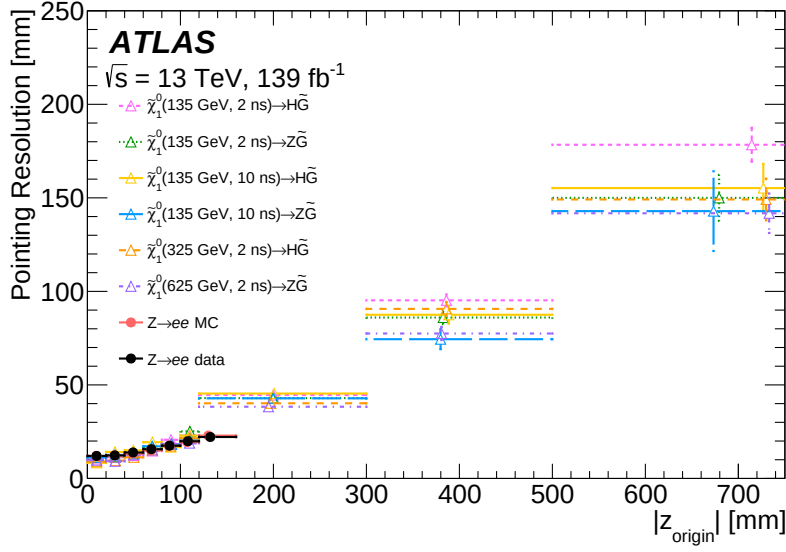


Figure 8.11: Resolution of the photon pointing variable as a function of $|z_{\text{origin}}|$ in units of mm.

8.2.3 Calo-Vertexing

Calo-vertexing builds off of the photon pointing procedure to reconstruct a secondary vertex, which corresponds to the production vertex of di-EM objects. Therefore, the localization of the di-EM vertex is done through the intersection of a pair of "photon lines", as shown in Figure 8.12. The illustration demonstrates a pair-produced non-pointing photon reconstructed in the EMB calorimeter. For each photon, the two barycenter positions are used to construct a line that is extrapolated back to the beamline. The point of intersection of the pair of lines is the diphoton production vertex, labeled the *secondary vertex (SV)*. The projections of the SV along the z-direction and in the transverse plane are called V_z and V_r , respectively. Here, V_z is measured as the distance from the primary vertex. The distance between the secondary vertex and the primary vertex, ρ , is defined as

$$\rho = \sqrt{V_r^2 + V_z^2} \quad (8.7)$$

The calo-vertexing algorithm rotates all photon measurements onto the $\phi = 0$ plane, and finds the intersection of the two photon paths obtained from the pointing calculation, as shown in Figure 8.12.

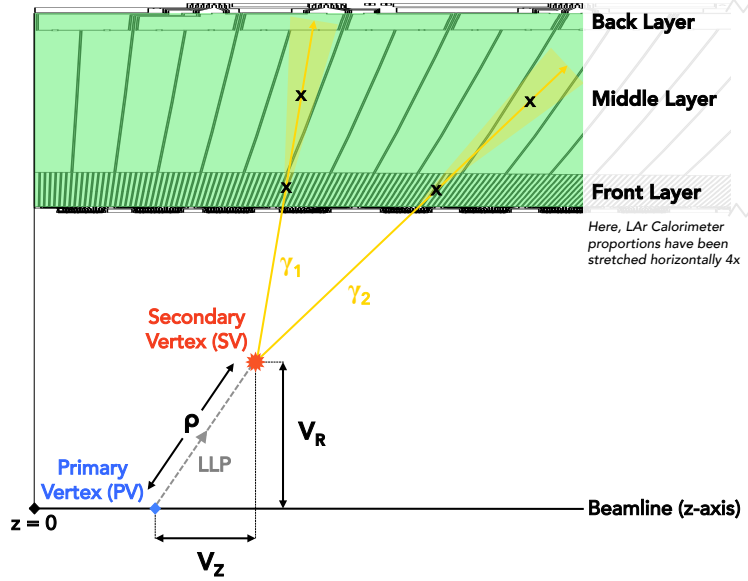


Figure 8.12: Illustration of the two-dimensional calo-vertexing procedure to calculate the V_r and V_z discriminating variables. The three layers of the LAr calorimeter are highlighted, along with the energy deposits left by the passage of the two daughter photons γ_1 and γ_2 of the LLP. The location of the secondary vertex (SV) is determined by the pointing measurements of the two photons. V_r is defined as the distance in R from the SV to the beamline, and V_z as the distance in z from the SV to the PV.

Figure 8.13 shows the V_r and V_z distributions for data and two signal points—HyyHSM and ZeeZSM—generated at $m(\tilde{\chi}_1^0) = 135$ GeV, $\tau(\tilde{\chi}_1^0) = 10$ ns. The distributions of the calo-vertexing variables clearly show the difference between the signal and background photons. The signal photons tend to be displaced from the PV and thus have a broad distribution; whereas the background photons are produced at the PV and thus have a narrow distribution⁵.

Since the calo-vertexing algorithm rotates all measurements to the $\phi = 0$ plane, the localization of the secondary vertex is in two dimensions. Several three-dimensional algorithms were attempted, however, the resolution of the calorimeter in the ϕ -direction is insufficient to precisely determine the secondary vertex in three dimensions.

⁵The asymmetry in the V_r distribution between data and signal events is due to the $\Delta\eta(\gamma_1, \gamma_2) > 0.1$ selection applied to improve the vertex resolution without significantly reducing signal reconstruction efficiency.

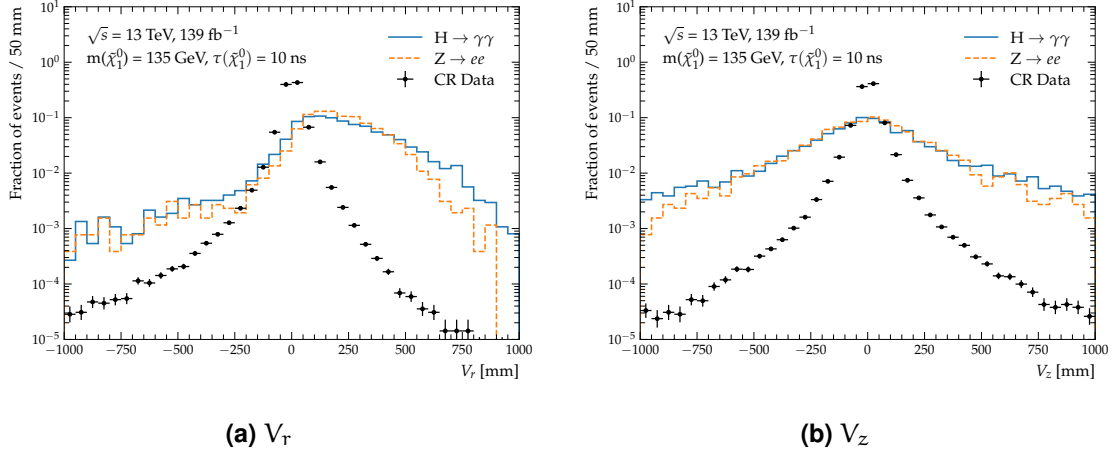


Figure 8.13: Distributions of the 2D displacement variables, V_r and V_z , for the data and two signal points—HyyHSM and ZeeZSM—generated at $m(\tilde{\chi}_1^0) = 135$ GeV, $\tau(\tilde{\chi}_1^0) = 10$ ns.

8.2.4 Vertexing Resolution

The calo-vertexing procedure is validated by comparing the vertexing distributions for $Z \rightarrow ee$ events in both data and simulation. The $Z \rightarrow ee$ events are required to pass at least one photon trigger, with at least two electrons passing selections listed in Table 8.3. Figure 8.14 shows the distribution of V_r , V_z , and ρ for $Z \rightarrow ee$ data and simulation. A good agreement is observed between the distributions from data and simulation.

Parameter	Cut Value
Electron multiplicity	≥ 2
Identification	Medium
Isolation	FCLoose
$ \eta $	< 2.47 (excluding $1.37 < \eta < 1.52$)
p_T	> 10 GeV
$ z_0 \cdot \sin \theta $	< 0.5 mm
$ d_0 / \sigma(d_0)$	< 3 mm
m_{ee}	$(68, 108)$ GeV
$ \Delta\eta(e_1, e_2) $	> 0.1

Table 8.3: Electron object selections for $Z \rightarrow ee$ events.

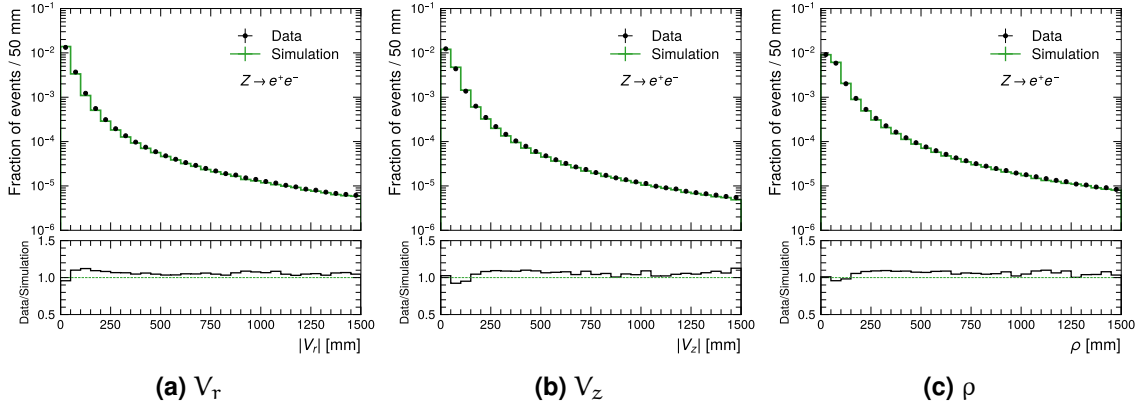


Figure 8.14: Calo-vertex distributions, V_T , V_Z , and ρ , for $Z \rightarrow ee$ events in data and simulation. The top plot shows the distributions observed from events in data and in simulation. The bottom plot shows the ratio of the data-to-simulation distributions.

Analogous to the calculation of pointing resolution, the vertexing resolution is calculated by fitting a Gaussian distribution to the V_T and V_Z distributions as a function of various kinematic variables. The variable with the most significant impact on the vertexing resolution is the difference in η between the two electrons, $\Delta\eta_{ee}$, as shown in Figure 8.15.

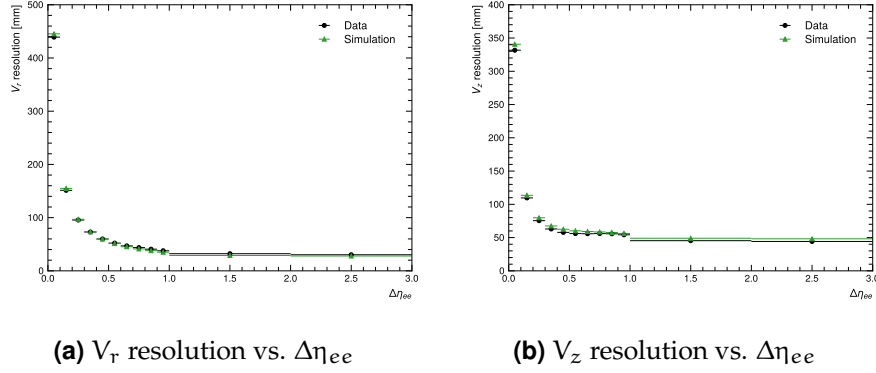


Figure 8.15: Resolution of the V_r and V_z as a function of $\Delta\eta_{ee}$ for $Z \rightarrow ee$ data and simulated events.

For low angular separations, i.e., for low $\Delta\eta$ values, the electron "paths" are nearly parallel; thus, the uncertainties in the determination of the barycenter positions are large enough to degrade the resolution of the V_r and V_z measurements. A selection on the $\Delta\eta_{ee}$ significantly improves the vertexing, as shown in Figure 8.16. The motivation for the $\Delta\eta_{ee}$ selection is explained in detail in Section 9.1.

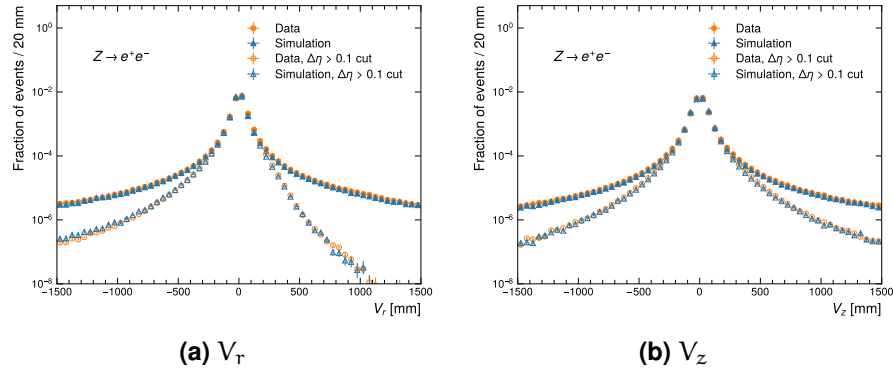


Figure 8.16: Effect of a $\Delta\eta$ cut on the V_r and V_z distributions for $Z \rightarrow ee$ data and simulation.

The performance of calo-vertexing also depends on the location of the EM objects across the detector. The reconstructed electron can be reconstructed either in the barrel (B) or in the endcap (E); the pair of $Z \rightarrow ee$ electrons can be classified into the following categories—BB, BE, and EE. Figure 8.17 shows the distribution of the V_r and V_z variables for different combinations of the detector regions. As evident from the figure, calo-vertexing works best for BE electrons, followed by BB, and EE electrons. The $\Delta\eta_{ee}$ selection also improves the agreement between the BB and BE V_r and V_z distributions.

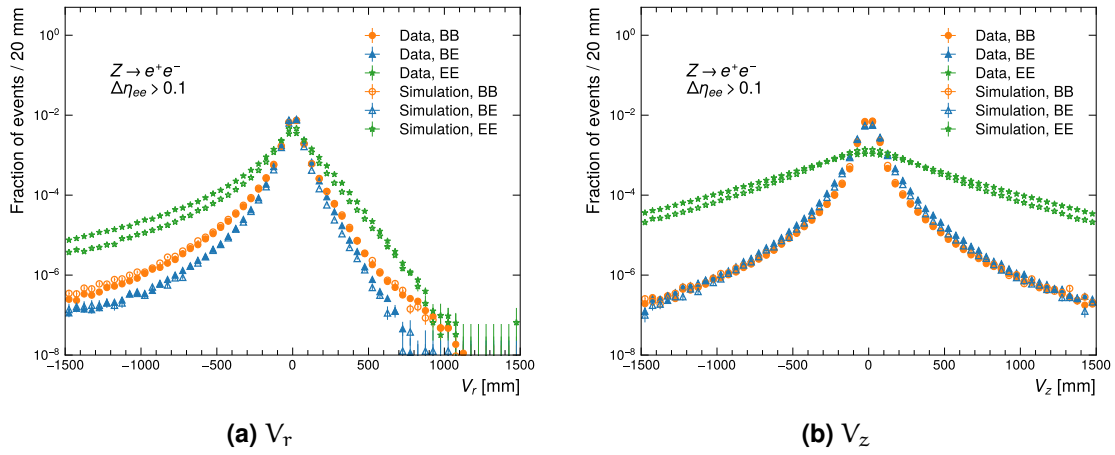


Figure 8.17: V_r and V_z distributions for different detector regions for $Z \rightarrow ee$ data and simulation. The events are classified into four categories based on the detector region where each of the two photons is reconstructed. Events, where both photons are reconstructed in the barrel region, are classified as BB; events, where both photons are reconstructed in the endcap region, are classified as EE. Events, where the higher- p_T photon is reconstructed in the barrel region, are classified as BE.

The two discriminating variables, timing, and vertexing, obtained from the LAr information are described in this chapter. The online timing measurement is corrected through an iterative offline timing calibration. This offline timing calibration results in a timing resolution in the range of 190–240 ps; a sub-nanosecond timing resolution enhances the search for delayed photons/electrons expected from the GMSB model studied in this thesis. A novel vertex-reconstruction algorithm that relies only on the LAr EM energy deposition information provides an excellent localization of the displaced production vertex of the signal photons/electrons. The V_r and V_z positions of the displaced vertex, along with the two-photon times will be shown to provide excellent signal-to-background discrimination.

Chapter 9

Analysis Strategy

This led to a debate between the two men on the differences between what was probable, plausible, and possible

Amor Towles
A Gentleman in Moscow

This chapter explains the event selection, and the definition of the various analysis regions which are used to estimate the background contribution, validate the background modeling, and perform the signal hypothesis test. Section 9.1.1 outlines the trigger, identification, object isolation, and kinematic selections applied to the photon objects. Section 9.2 outlines the analysis regions defined for the background modeling, validation of the background model, and the signal region. Section 9.3 details the sensitive variables which are used in the statistical framework.

9.1 Event Selection

9.1.1 Photon Object Selection

The thesis uses photon objects to reconstruct both displaced photons and electrons. The object selections are applied to all signals, regardless of the final state, $H \rightarrow \gamma\gamma$ or $Z \rightarrow ee$. The motivation to reconstruct electron candidates as photon objects is that a displaced electron produced in or beyond the pixel detector may lack the necessary ID hits to definitively identify the object as an electron (cf. Section 6.2.2). In the case of an electron-photon ambiguity, the overlap removal procedure (cf. Section 6.2.6) prioritizes photon reconstruction. Since the standard ATLAS photon reconstruction, identification, and isolation algorithms focus on prompt, pointing photons, a careful choice of the photon isolation and identification working points is required for non-prompt, non-pointing photons.

Photon Identification

Since the displaced photons are non-projective with respect to the origin, the nature of non-pointing photons motivates a careful choice of the identification (ID) method chosen for the photons under analysis. The Tight ID imposes cuts on the shower shape variables which significantly reduces the efficiency of the identification for non-pointing photons. Previous non-pointing photon analyses have shown the less restrictive Loose ID to be less biased against non-pointing photons [76, 78]. Therefore, the Loose or the Medium ID working points which apply less strict object requirements are good candidates for photon identification.

The ATLAS Run 2 trigger menu [92] provides several diphoton triggers, each with a distinct ID working point and a set of p_T thresholds for the leading (highest- p_T) and subleading (second highest- p_T) photons. Therefore, the choice of ID which maximizes the signal acceptance is linked to the set of p_T thresholds defined for the photon triggers.

In 2015–2016, HLT_g35_loose_g25_loose was used at the HLT for the primary diphoton trigger. In 2017–2018, the Medium working point was employed instead of the Loose working point to maintain the rate of the diphoton trigger below 20 Hz at higher instantaneous luminosity. Thus, the p_T threshold of the loose diphoton trigger was increased to 50 GeV.

The efficiency of the diphoton trigger for the Loose and Medium ID working points is shown in Figure 9.1. The trigger efficiency for the HyyHSM and ZeeZSM signal samples generated at various $\tilde{\chi}_1^0$ masses and at $\tau(\tilde{\chi}_1^0) = 2$ ns are shown. As evident from the figure, the Medium ID working point outperforms the Loose working point for both the HyyHSM and ZeeZSM signal samples. Since the Medium trigger requires the lower p_T thresholds compared to the Loose trigger, the trigger efficiency of the Medium working point is higher. Additionally, since $m(Z) < m(H)$, the $Z \rightarrow ee$ electrons would be softer compared to the $H \rightarrow \gamma\gamma$ photons; the trigger efficiency for the HyyHSM signal is higher than that of the ZeeZSM signal given the expected p_T -spectra of the di-EM objects.

Therefore, the Medium diphoton trigger and ID working points are employed for the analysis. The leading (subleading) photon must have $p_T > 40$ GeV (> 30 GeV)—5 GeV greater than the threshold to ensure all events are on the trigger efficiency plateau (cf. Figure 7.1).

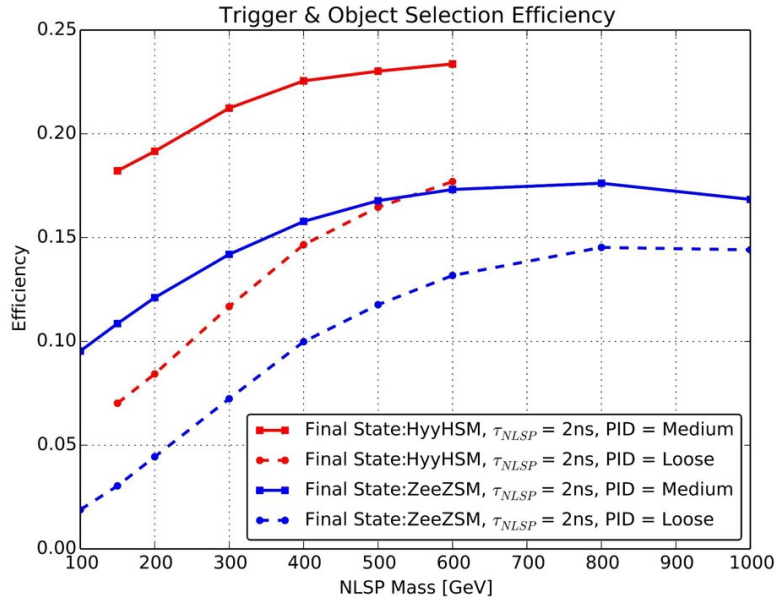


Figure 9.1: Trigger efficiencies for the Loose and Medium diphoton triggers as a function of the $\tilde{\chi}_1^0$ mass. The trigger efficiencies are calculated for the HyyHSM and ZeeZSM final states with $\tau(\tilde{\chi}_1^0) = 2\text{ ns}$. The events are required to pass the trigger p_T and photon ID requirements.

Photon Isolation

Photon isolation eliminates photon candidates with a high amount of surrounding calorimeter activity. Several isolation working points were studied to provide maximal signal acceptance without introducing significant bias against the photon pointing or timing. The available photon isolation working points, along with their definitions in terms of the calorimeter and track isolation requirements are listed in Table 6.8. Figure 9.2 shows the photon isolation efficiency as a function of the photon time and pointing for the HyyHSM signal samples generated at $\tau(\tilde{\chi}_1^0) = 2$ ns. As evident from the figure, the FixedCutLoose isolation working point provides good signal acceptance while minimizing the bias against photon pointing or timing. Therefore, the FixedCutLoose isolation working point is employed for the photon object isolation.

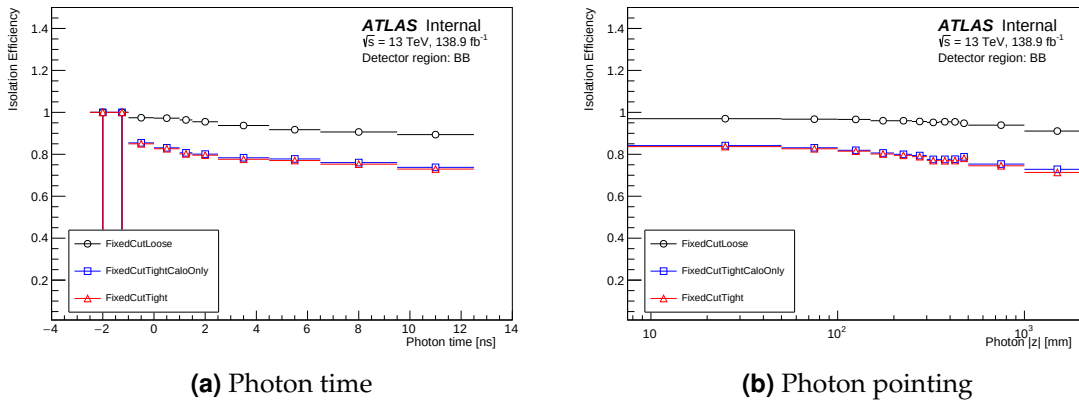


Figure 9.2: Photon isolation efficiency as a function of the photon time and pointing. The efficiencies of the three different working points are calculated for the HyyHSM signal points with the $\tau(\tilde{\chi}_1^0) = 2$ ns decay lifetime; signal samples generated at different mass points are added together to improve the statistics in determining the efficiencies. The events are required to pass the p_T requirements defined by the triggers, and the photon identification requirement and both the photons are measured in the barrel region of the EM calorimeter.

Photon Timing

The offline timing calibration (cf. Section 8.1) is applied to the photon timing information. Therefore, the photon objects are required to be read out in the MEDIUM or HIGH signal gain. The Low gain timing events are rejected and have a minimal impact on signal efficiency.

A selection on the photon timing of $|t(\gamma)| < 12$ ns, is also required. In data, this timing selection rejects photons originating from collisions from neighboring bunch crossings at ± 25 ns. In simulation, the modeling of delayed objects arises when their measured time is 12.5 ns. Therefore, the selection of $|t(\gamma)| < 12$ ns rejects mismodeled events in simulation. The selection on the timing has a negligible impact on the signal efficiency because: (1) the exponential nature of the LLP decay implies that only a small fraction of the LLPs decay at times greater than 12 ns. (2) LLPs that decay in or outside the LAr calorimeter volume are not reconstructed properly or tend to escape detection.

Reconstructed photons are required to have $E_{\text{cell}}^{\text{maxE}} > 5$ GeV, which reduces very low-energy EM objects with a poor timing resolution as shown in Figure 8.8.

Photon Kinematics

Events must have at least two photons satisfying the selections in 9.1.1 and should be matched to the diphoton trigger listed in Section 7.1.2. Since the diphoton triggers have p_T thresholds of 35 and 25 GeV, a selection on the diphoton invariant mass, $m_{\gamma\gamma} > 60$ GeV, is applied. Events with two endcap photons (EE) have a poor vertex resolution (cf. Section 8.2.3) and are thus rejected. As shown in Figure 8.15, the vertex resolution depends on the η -difference between the two photons, therefore a selection of $\Delta\eta_{\gamma\gamma} > 0.1$ is applied. The selection on $\Delta\eta_{\gamma\gamma}$ reduces events with poorly resolved reconstructed vertices. Events must also satisfy $0 < V_T < 1500$ mm and $|V_z| < 3740$ mm to veto vertices reconstructed far beyond the inner detector.

A summary of the photon object selections is listed in Table 9.1.

9.2 Analysis Region Definitions

Events that pass the event selection described in the previous section are organized into statistically independent analysis regions. The *Control Region (CR)* is used to derive the background estimation with a large sample size while maintaining negligible signal contamination. The *Validation Regions (VRs)* help validate the background estimation and the statistical analysis, while also being depleted in the signal. Finally, the *Signal Region (SR)* defines the analysis region-of-interest for the search. The timing and vertexing distribution in the SR were blinded throughout the development and finalization of the background estimation.

The analysis regions are defined using several event-level variables— E_T^{miss} , photon timing, $m_{\gamma\gamma}$, diphoton transverse momentum ($p_T^{\gamma\gamma}$), and diphoton azimuthal separation ($\Delta\phi(\gamma_1, \gamma_2)$). These variables and their specific selections for each analysis region are described below.

Parameter	Selection Value
Photon multiplicity	≥ 2
Photon η	$ \eta < 1.37 \parallel 1.52 < \eta < 2.37$ (≥ 1 with $ \eta < 1.37$)
$E_{\text{cell}}^{\text{maxE}}$ GeV	> 5
Leading (subleading) p_T [GeV]	> 40 (> 30)
Identification	Medium
Isolation	FixedCutLoose
Gain	MEDIUM or HIGH
Timing [ns]	$\in (-12, 12)$
$\Delta\eta_{\gamma\gamma}$	> 0.1
$m_{\gamma\gamma}$ [GeV]	> 60
V_T [mm]	$\in (0, 1500)$
$ V_z $ [mm]	< 3740

Table 9.1: Summary of the photon object selections.

Missing Transverse Energy (E_T^{miss})

In the signal model, E_T^{miss} arises because of the momentum carried by the $\tilde{G}$ which escapes detection, and also due to the momentum carried by neutrinos. For SUSY models, the presence of significant missing energy is one of the vital signatures of the physics process. Figure 9.4a shows the E_T^{miss} distribution for the signal-depleted data and several HyyHSM and ZeeZSM signal samples. As expected, the E_T^{miss} spectrum is harder for higher $\tilde{\chi}_1^0$ masses and lifetimes. Therefore, a selection on the event-level E_T^{miss} is used to assign the event to the proper analysis region.

Photon Timing

The timing information is one of the sensitive variables employed in the event selection. The prompt background timing distribution is symmetric and centered about zero. In contrast, the signal events include leading and subleading photon times ($t_{\gamma 1}$ and $t_{\gamma 2}$) with positive times. Therefore, the regions with $t_{\gamma 1}, t_{\gamma 2} < 0$ have very low signal contamination. A selection on the *sign* of the photon times provides a good handle on the region definition.

Based on the sign of the two photon times, four timing quadrants, visualized in Fig 9.3, can be defined. The quadrants are pospos ($t_{\gamma 1} > 0$ and $t_{\gamma 2} > 0$), posneg ($t_{\gamma 1} > 0$ and $t_{\gamma 2} < 0$), negpos ($t_{\gamma 1} < 0$ and $t_{\gamma 2} > 0$), and negneg ($t_{\gamma 1} < 0$ and $t_{\gamma 2} < 0$). It was found that the background timing distribution is symmetric about $t = 0$ (cf. Appendix B); therefore, the CR makes use of both pospos and negneg quadrants to derive the background model.

Diphoton Mass, Momentum, and Angular Separation

Selections on the kinematic properties of the di-EM objects are also used to classify events into the analysis regions. The diphoton mass for the signal-depleted data and for several HyyHSM and ZeeZSM signal samples is shown in Figure 9.4b. As evident from the figure, the $m_{\gamma\gamma}$ distribution peaks at 125 GeV (91 GeV) for the $H \rightarrow \gamma\gamma$ ($Z \rightarrow ee$) decay mode. The $m_{\gamma\gamma}$ distributions exhibit a slowly falling low-mass tail because the calculation of the invariant mass assumes the decay occurs at the PV, and thus underestimates the opening angle between the two EM objects.

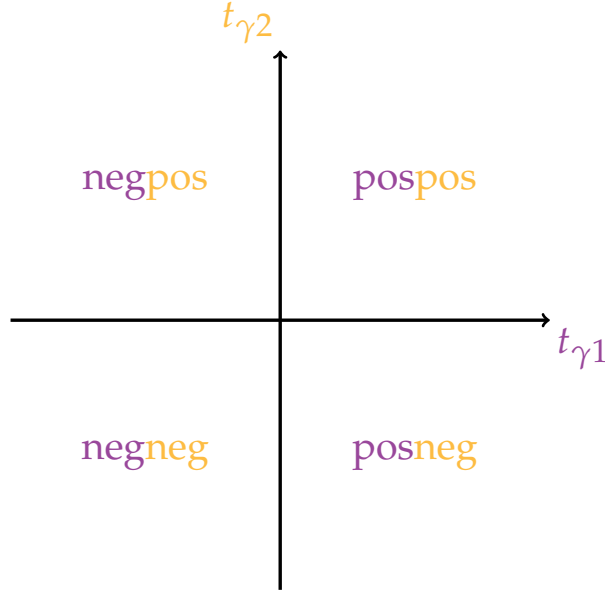


Figure 9.3: Illustration of the timing quadrants based on the sign of the photon times.

Figure 9.4c shows the $p_T^{\gamma\gamma}$ distributions, and Figure 9.4d shows the $\Delta\phi(\gamma_1, \gamma_2)$ distributions of the signal-depleted data and signal samples. The final-state EM objects are Lorentz-boosted because of their parent Higgs (Z) boson; thus, the $p_T^{\gamma\gamma}$ distribution for the signal samples is harder compared to the distribution observed in the data. Since the $p_T^{\gamma\gamma}$ and $\Delta\phi(\gamma_1, \gamma_2)$ provide modest signal-to-background discrimination, an event-level selection on these variables is applied to enhance the signal acceptance for the SR.

9.2.1 Summary of Analysis Regions

The SR is optimized for signal sensitivity and is defined by: $E_T^{\text{miss}} > 30 \text{ GeV}$, $m_{\gamma\gamma} < 135 \text{ GeV}$, $p_T^{\gamma\gamma} > 70 \text{ GeV}$, $\Delta\phi(\gamma_1, \gamma_2) < 2.4$, and $t_{\gamma 1} > 0$ and $t_{\gamma 2} > 0$.

The CR is defined by flipping the requirement on the E_T^{miss} and removing the selections on the $p_T^{\gamma\gamma}$ and $\Delta\phi(\gamma_1, \gamma_2)$. The selection on the $m_{\gamma\gamma}$ is also flipped, to keep blind the low- $m_{\gamma\gamma}$ events for future analysis. The pospos and negneg timing quadrants are used in the CR to increase the statistics for the background modeling. The CR is defined as: $E_T^{\text{miss}} < 20 \text{ GeV}$, $m_{\gamma\gamma} > 135 \text{ GeV}$, and $t_{\gamma 1} \times t_{\gamma 2} > 0$.

The analysis uses three VRs defined to validate the kinematic and photon-

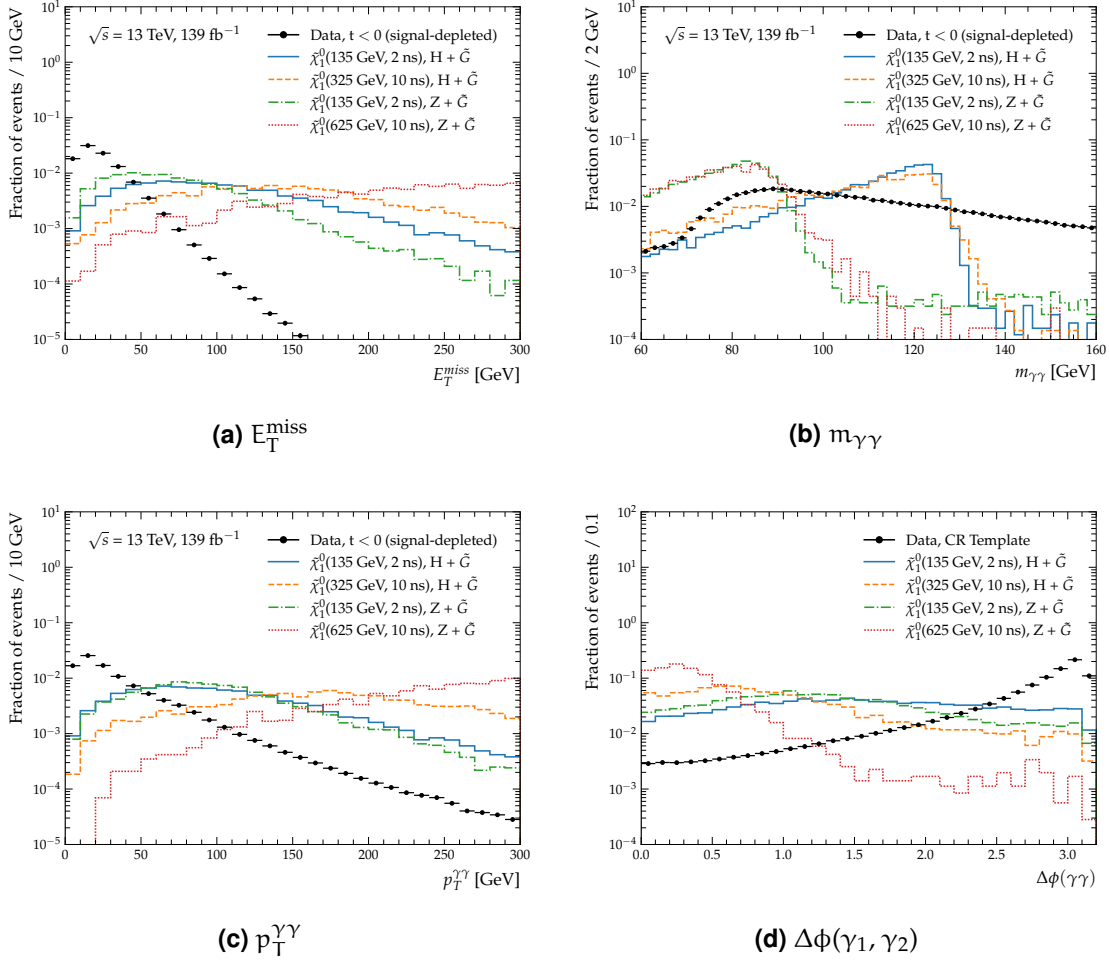


Figure 9.4: Distributions of event-level variables used to define the analysis regions. The distributions for the signal-depleted data and the various MC signal samples are shown. Event preselections, listed in Table 9.1, are applied to both the data and the signal samples. The signal samples are labeled by the $\tilde{\chi}_1^0$ mass and lifetime, $\tilde{\chi}_1^0(m, \tau)$, and the decay mode of the forced $\tilde{\chi}_1^0$ decay.

timing differences between the CR and SR. A mid- E_T^{miss} VR is defined to validate the extrapolation of the background model across different E_T^{miss} regions. Similarly, a VR with kinematic selections identical to the SR but with the requirement of negneg photons is defined to validate the extrapolation of the background model from the CR to the SR. The mid- E_T^{miss} VR, $VR-E_T^{\text{miss}}$, is defined as: $E_T^{\text{miss}} \in [20, 30)$ GeV, $m_{\gamma\gamma} > 135$ GeV, and $t_{\gamma 1} \times t_{\gamma 2} > 0$. The high- E_T^{miss} VR, $VR\text{-time}$, is defined as: $E_T^{\text{miss}} > 30$ GeV, $m_{\gamma\gamma} < 135$ GeV, $p_T^{\gamma\gamma} > 70$ GeV, $\Delta\phi(\gamma_1, \gamma_2) < 2.4$, and $t_{\gamma 1} < 0$ and $t_{\gamma 2} < 0$.

A visual illustration of the analysis regions is shown in Figure 9.5. Table 9.2 shows the selections of the event-level variables for the various analysis regions, and their observed Run 2 yields.

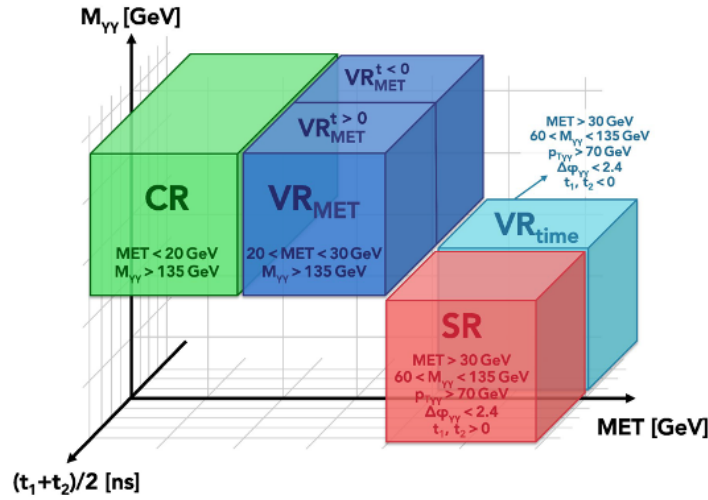


Figure 9.5: Illustration of the analysis regions in three-dimensional— E_T^{miss} , $m_{\gamma\gamma}$, and photon-time—phase space. The illustration only includes the pospos and negneg events.

Besides these analysis regions, an additional region is defined to provide a model-independent interpretation of the results. The discovery region, SR_{disc} , is defined in the high-timing regime ($0.9 < t_{\text{avg}} < 12$ ns) of the SR. The region contains no selections on the vertexing variables (except those applied at the preselection), which allows for a model-independent search.

9.3 Sensitive Variables

The timing information from the LAr calorimeter and the two-dimensional vertex location are the key variables for this search. The search uses the correlations between these sets of measurements to develop two sensitive variables— t_{avg} and ρ .

The timing distributions of the leading and the subleading photons are shown in Figures 9.6a, 9.6b. In the figure, events from the CR data and the SR data from the simulated signal samples are shown. The signal samples are the HyyHSM and the ZeeZSM decay modes with the following combination of the $\tilde{\chi}_1^0$ mass and lifetime: (135 GeV, 2 ns) and (325 GeV, 10 ns) for the HyyHSM samples, and (135 GeV, 2 ns) and (625 GeV, 10 ns) for the ZeeZSM sample. As evident from the figure, the signal events have a positive time-of-arrival and also have a broader timing distribution compared to the distribution of the CR events. The timing correlations between the signal photons are more evident in Figure 9.6d which shows the two-dimensional distribution of the two SR-photon timing measurements. Contrast with Figure 9.6c, which shows the two-dimensional distribution of the two CR-photon timing measurements. For the CR events, there is a weak correlation between the timing measurements of the two photons because of the beamsread. However, there is a clear correlation between the two signal photon timing measurements since these photons are pair-produced by a common particle, the $\tilde{\chi}_1^0$.

Parameter	CR	VR- E_T^{miss}	VR-time	SR
E_T^{miss} [GeV]	< 20	$\in [20, 30)$	> 30	> 30
$m_{\gamma\gamma}$ [GeV]	> 135	> 135	(60, 135)	(60, 135)
Sign of t_γ	$t_{\gamma 1} \times t_{\gamma 2} > 0$	$t_{\gamma 1} \times t_{\gamma 2} > 0$	$t_{\gamma 1}, t_{\gamma 2} < 0$	$t_{\gamma 1}, t_{\gamma 2} > 0$
$p_T^{\gamma\gamma}$ [GeV]	-	-	> 70	> 70
$\Delta\phi(\gamma_1, \gamma_2)$	-	-	< 2.4	< 2.4
Data Yield	221,605	109,122	18,260	18,276

Table 9.2: Event-level selections for the analysis regions and their corresponding Run 2 yields.

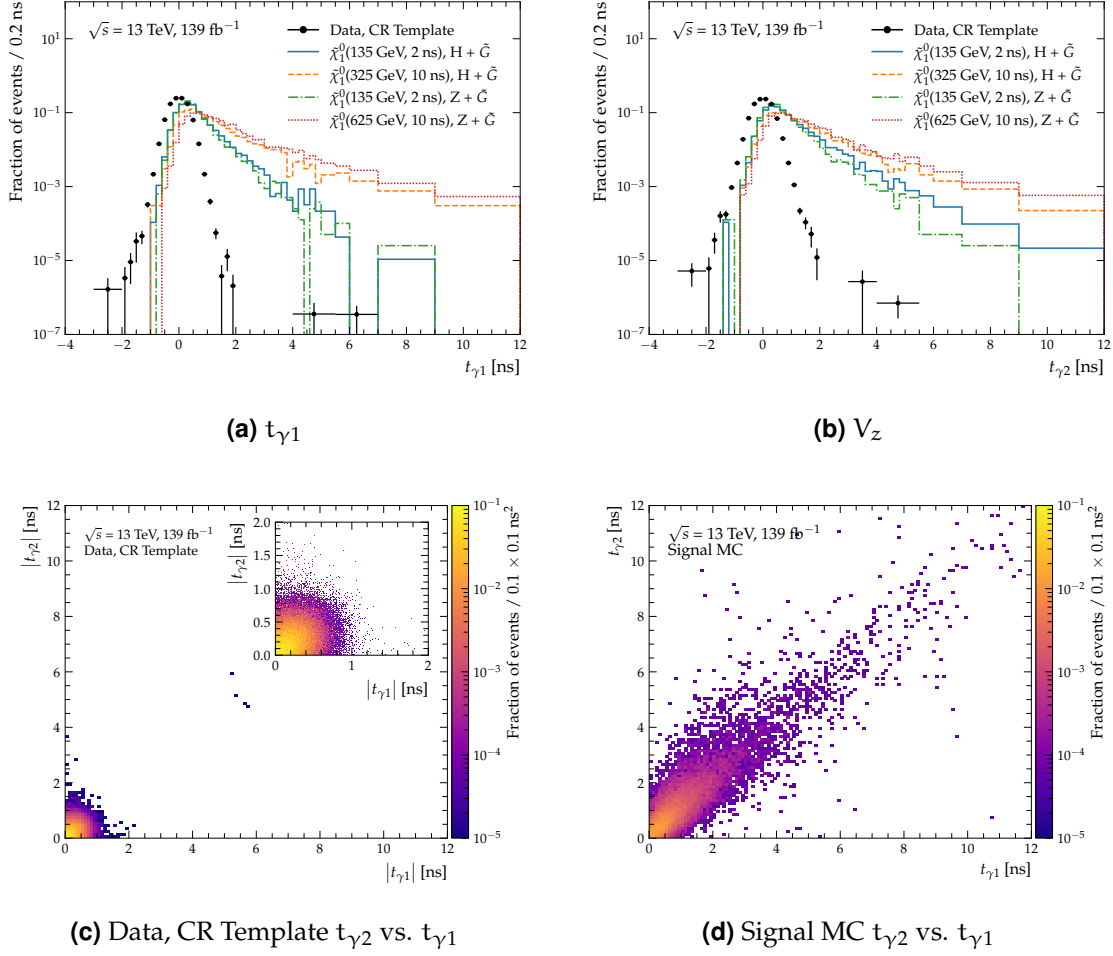


Figure 9.6: Comparison of the two photon timing distributions for signal and data. The signal photons have positive values and have a broader timing distribution than those of the CR photons.

Therefore, the search combines the timing information for the two photons to define the absolute-value average of the two photon times, t_{avg} :

$$t_{\text{avg}} \equiv \frac{1}{2} |t_{\gamma 1} + t_{\gamma 2}| \quad (9.1)$$

The absolute-valued average accounts for the negneg photons which are a part of the CR, VR- E_T^{miss} , and VR-t analysis regions.

The V_r and V_z vertexing distributions are shown in Figures 9.7a and 9.7b. These

distributions highlight the power of the calo-vertexing method. Signal events, which are produced with the decay of the long-lived $\tilde{\chi}_1^0$, are visibly different from the promptly produced background events. The correlation between the vertexing variables is shown in Figure 9.7c for the CR events and in Figure 9.7d for the SR events. In data, events which are mis-reconstructed in one direction are also very likely to be mis-reconstructed in the other direction. However, for signal events where the $\tilde{\chi}_1^0$ has a non-zero decay lifetime, the secondary vertex is displaced in both R and z directions.

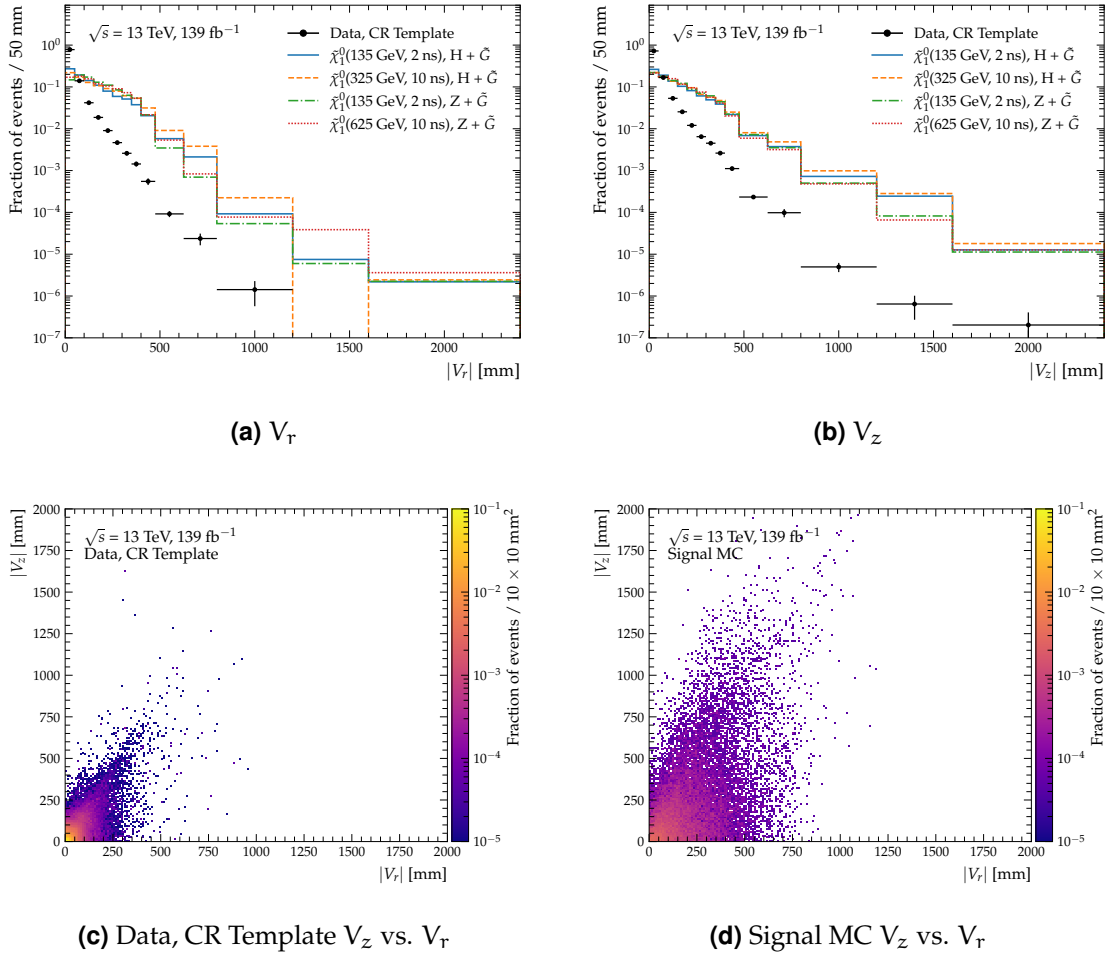


Figure 9.7: Comparison of vertexing distributions for signal and data.

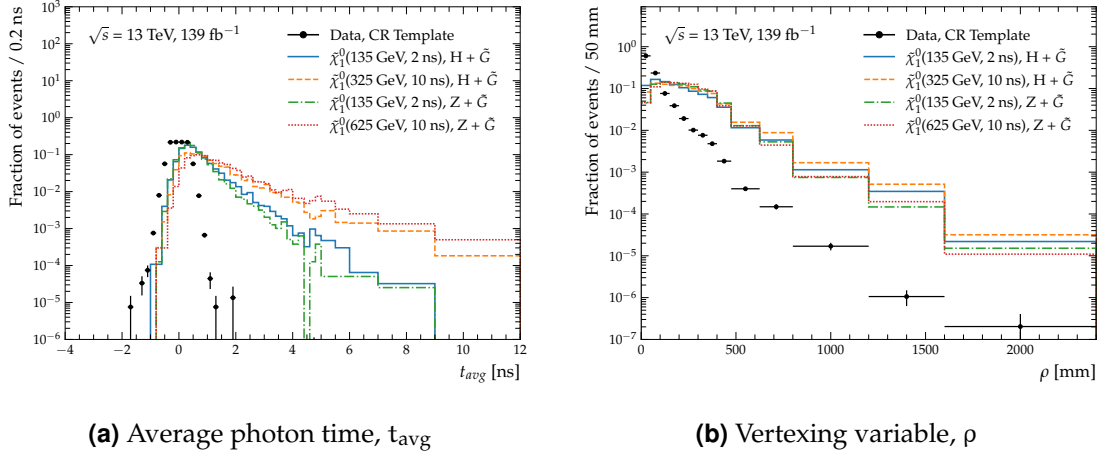


Figure 9.8: Sensitive analysis variables— t_{avg} and ρ —for CR events in data and SR events in simulation.

Therefore, the search combines the vertexing information in the R and z directions to define the displacement, ρ :

$$\rho \equiv \sqrt{V_r^2 + V_z^2} \quad (9.2)$$

Figure 9.8 shows the t_{avg} and ρ distributions for the events in data passing the CR selections, and events in signal samples passing the SR selections. Note, t_{avg} distribution has a distinct "flat-top" that is an artifact of the selection on the photon time, i.e., requiring pospos and negneg photons. Therefore, the entries of t_{avg} near zero are less populated since the cancellation from posneg and negpos timing quadrants are absent. The sensitive variables, the timing, and the vertexing information were combined in different combinations. However, t_{avg} and ρ were the best-performing variables for signal-to-background discrimination.

The choice of bins for the sensitive variables was determined through an optimization procedure designed to maximize the signal sensitivity. The optimized choice of the *analysis binning* for both the t_{avg} and ρ variables are:

$$t_{\text{avg}} \text{ bins: } [0.0, 0.2, 0.4, 0.6, 0.9, 12.0] \text{ ns} \quad (9.3)$$

$$\rho \text{ bins: } [0, 80, 160, 300, 520, 2000] \text{ mm} \quad (9.4)$$

The choice of bins for the ρ variable is used to define the five regions, in bins of ρ , to be used in the likelihood fit. Figure 9.9 shows the distributions of t_{avg} and ρ in the optimized choice of bins.

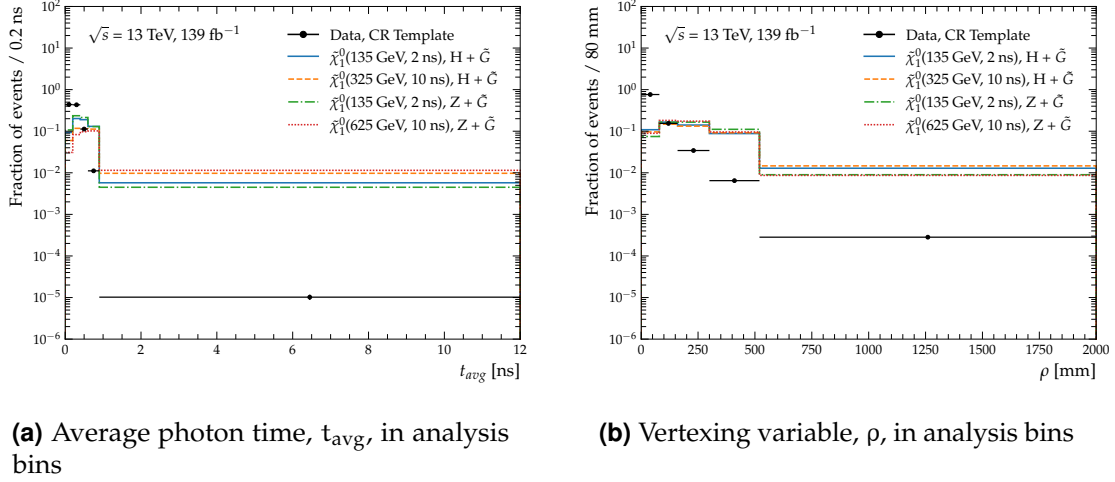


Figure 9.9: Sensitive analysis variables— t_{avg} and ρ —in the optimized analysis bins.

To summarize, this chapter described the event-level selections, the analysis regions, and the optimized choice of bins for the sensitive variables. The event-level selections, the analysis regions, and the optimized choice of bins for the sensitive variables are presented in Table 9.3. The following chapter describes the background estimation procedure which describes how the distribution of the background events in the signal region is modeled using the events in the control region. The validation region is used to verify the extrapolation of the background distribution from the control to the signal region.

In the following chapter, the background estimation procedure is described. The low- E_T^{miss} CR is used to derive the background model for the high- E_T^{miss} SR. The background model consists of the t_{avg} distribution sliced in categories of ρ . The shape of the t_{avg} distribution in each ρ category is called a "*template*". The following chapter describes how the background templates are constructed and processed.

Parameter	Preselection requirements			
Photon multiplicity	≥ 2			
Photon η	$ \eta < 1.37 \parallel 1.52 < \eta < 2.37 (\geq 1 \text{ with } \eta < 1.37)$			
$E_{\text{cell}}^{\text{maxE}}(\gamma)$ [GeV]	$E_{\text{cell}}^{\text{maxE}}(\gamma_1), E_{\text{cell}}^{\text{maxE}}(\gamma_2) > 5$			
$p_T(\gamma)$ [GeV]	$p_T(\gamma_1) > 40, \ p_T(\gamma_2) > 30$			
$\Delta\eta_{\gamma\gamma}$	> 0.1			
$m_{\gamma\gamma}$ [GeV]	> 60			
V_r [mm]	< 1500			
$ V_z $ [mm]	< 3740			
t_γ [ns]	$t_{\gamma 1}, t_{\gamma 2} \in (-12, 12)$			
Parameter	Analysis region requirements			
	CR	VR($E_{\text{T}}^{\text{miss}}$)	VR(t)	SR
$E_{\text{T}}^{\text{miss}}$ [GeV]	< 20	$[20, 30)$	> 30	
$m_{\gamma\gamma}$ [GeV]	> 135		$(60, 135)$	
Sign of t_γ	$t_{\gamma 1} \times t_{\gamma 2} > 0$		$t_{\gamma 1}, t_{\gamma 2} < 0$	$t_{\gamma 1}, t_{\gamma 2} > 0$
$p_{\text{T}}^{\gamma\gamma}$ [GeV]	-			> 70
$\Delta\phi(\gamma_1, \gamma_2)$	-			< 2.4
Vertexing and timing bins				
ρ bin edges [mm]	$[0, 80, 160, 300, 520, 2000]$			
t_{avg} bin edges [ns]	$[0, 0.2, 0.4, 0.6, 0.9, 12]$			

Table 9.3: Optimized requirements defining the preselection, SR, CR, and both VRs. Also included are the optimized binning for the photon vertexing ($\rho = \sqrt{V_r^2 + V_z^2}$) and average timing (t_{avg}) variables.

Chapter 10

Background Estimation

It is a profound and necessary truth
that the deep things in science are
not found because they are useful;
they are found because it was
possible to find them.

Rudolf Pierels

The Making of the Atomic Bomb

This chapter outlines the background estimation procedure, where the background model from the low- E_T^{miss} control region is extrapolated to the high- E_T^{miss} signal region. A good background estimation reduces the possibility of missing signal events, and false positives, without reducing signal sensitivity. Several procedures are applied to ensure the quality of the photons and their timing resolutions are consistent between the control and the signal regions. The background modeling is verified with the VR- E_T^{miss} and VR-time validation regions.

No SM processes result in a displaced diphoton signature. The background events in the signal regions arise from either real, mismeasured photons or jets which are mis-reconstructed as photons. These events result in the non-Gaussian tails in the timing distribution of the signal region events. Since the non-Gaussian tails are not properly modeled in the Monte Carlo simulation, a fully data-driven background estimation is used to predict the size and shape of these two background sources in the signal region.

An additional source of background is the events produced in satellite collisions described in Sections 8.1.5, 4.2. These satellite collisions produce delayed objects with times around ± 5 ns but are suppressed by roughly 10^6 with respect to the nominal bunch.

The low- E_T^{miss} CR is used to predict the shape of the average photon time in the high- E_T^{miss} SR. Additional processing to the CR t_{avg} distribution is performed to account for known kinematic dependencies and to provide a better estimation of

the shape of the background t_{avg} distribution in the SR. The background processing — purity rescaling, $E_{\text{T}}^{\text{miss}}$ reweighting, and residual time shift — are described below.

10.1 Purity Scaling

Previous non-pointing photon analyses [76, 78] have shown that the measured pointing and timing distributions of genuine photons are narrower than those of other physics objects (jets) that can be mis-reconstructed as photons. To capture this shape difference, two templates¹ are defined — one enriched in real photons and the other enriched in fake photons — by their respective selections on the photon identification. The real-enhanced selection, TIGHT-TIGHT, is defined by the CR selection in addition to a requirement that both photons satisfy the Tight identification criteria. Similarly, the fake-enhanced selection, ANTI-TIGHT-TIGHT, is defined as events where at least one photon fails the Tight identification. Figure 10.1a shows the distribution of the real- and fake-enhanced templates for the CR events. As evident in the figure, the distribution of the real-enhanced photons is narrower than the distribution of the fake-enhanced photons.

The purity fraction, f_{TT} , is defined as the fraction of TIGHT-TIGHT events in a given region; thus, by definition, $f_{\text{Anti-TT}} = 1 - f_{\text{TT}}$. The composition of the purity fraction changes as a function of the analysis region, and as a function of the ρ category, as shown in Figure 10.1b. Since the composition of f_{TT} changes, a reweighting is performed to match the purity fraction observed in the SR. The reweighting is performed inclusively in photon timing but is performed in exclusive bins of ρ . The observed f_{TT} in the SR ranges from approximately 0.8 in the lowest ρ category to approximately 0.5 in the highest ρ category.

10.2 $E_{\text{cell}}^{\text{maxE}}$ Reweighting

It is observed that the timing resolution is inversely related to the deposited cell energy (cf. Figure 8.8). Therefore, the $E_{\text{cell}}^{\text{maxE}}$ distributions of the leading and subleading photons in the CR are reweighted to match the $E_{\text{cell}}^{\text{maxE}}$ distributions observed in the SR. The reweighting is performed exclusively in the ρ categories

¹The shape of the t_{avg} distribution in one category of ρ is called a "template"

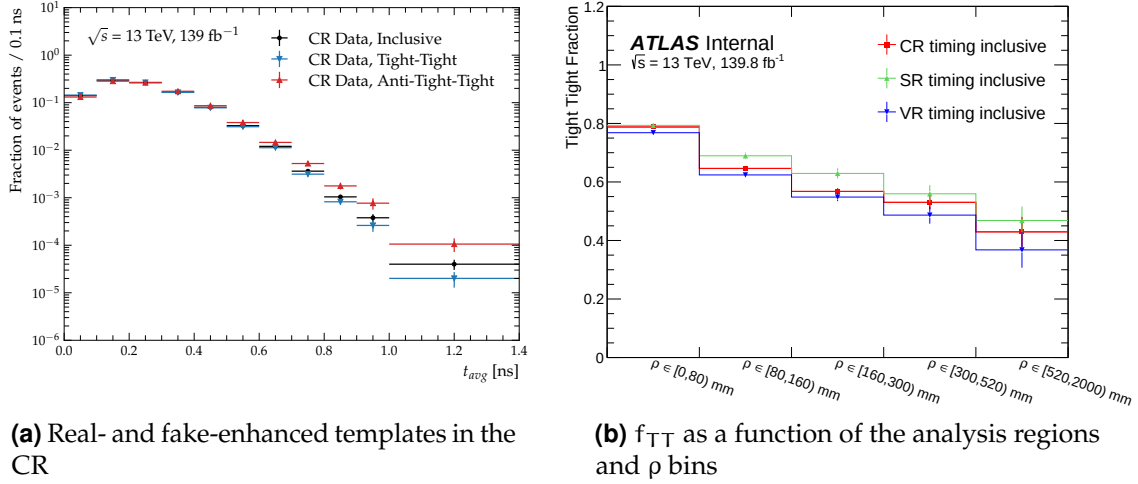


Figure 10.1: Average photon timing distribution for the CR events split into real- and fake-enhanced templates. The TIGHT-TIGHT fraction, f_{TT} , for the various analysis regions as a function of the ρ categories, is also shown.

and separately for both the real- and fake-enhanced templates. Since the signal photon $E_{\text{cell}}^{\text{maxE}}$ distributions will be correlated, a two-dimensional reweighting is performed. Figure 10.2 shows the distribution of the $E_{\text{cell}}^{\text{maxE}}$ reweights for the CR-to-SR reweighting. Most of the reweights fall in the range of 0.0–2.0 ($\sim 93\%$ of the total).

10.3 Residual Timing Shift

Although the timing calibration (cf. Section 8.1) centers the timing distributions about zero, residual timing corrections are applied to account for the small, $\mathcal{O}(\text{ps})$, shifts introduced by the application of timing corrections derived from electrons to photon objects. This timing correction is performed in a two-step procedure — first in bins of $E_{\text{cell}}^{\text{maxE}}$ and second in bins of ρ — for each of the three (CR, VR, and SR) analysis regions. This two-step correction amounts to a 5–10 ps shift to the photon timing distribution. Although these corrections are small, they significantly improve the agreement in the t_{avg} distributions across analysis regions. Figure 10.3 shows the size of the corrections applied to the leading and subleading photon timing distributions.

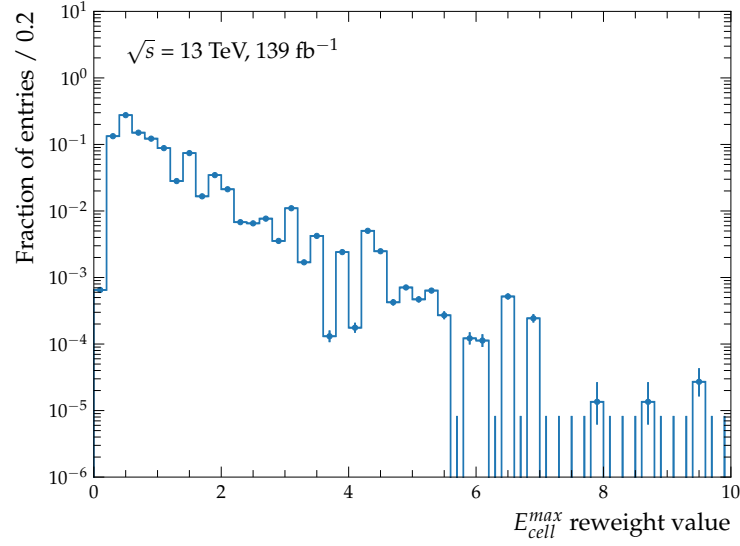


Figure 10.2: Distribution of the CR-to-SR $E_{\text{cell}}^{\text{maxE}}$ reweight values. $\sim 93\%$ of the reweight values are in the range 0.0–2.0.

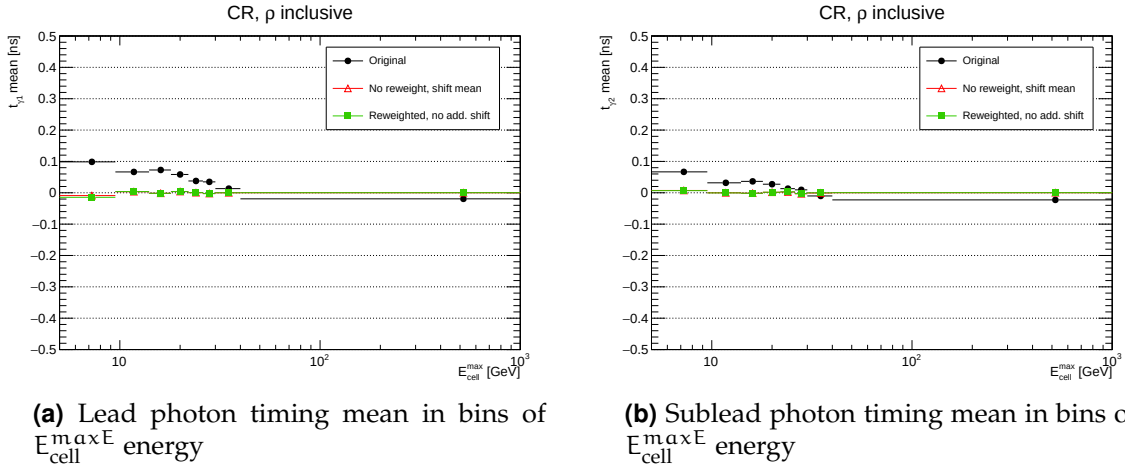


Figure 10.3: Distribution of the timing mean of the lead and sub-lead photons in bins of $E_{\text{cell}}^{\text{maxE}}$ energy. The individual photon timing distributions have a non-zero mean, shown by solid black points and labeled as "Original" in the plot. The timing distributions are then shifted to zero before performing the $E_{\text{cell}}^{\text{maxE}}$ reweight, shown by hollow red triangles and labeled as "No reweight, shift mean". After performing the $E_{\text{cell}}^{\text{maxE}}$ reweighting, the timing distributions are still centered about zero, shown by filled green squares and labeled "Reweighted, no. add. shift".

In summary, the background estimation consists of three processing steps: (1) purity scaling, (2) $E_{\text{cell}}^{\text{maxE}}$ reweighting, and (3) residual timing corrections. Each of these processes is performed inclusive in photon timing (pospos, negneg, posneg, and negpos photons) to maximize the available statistics of the CR. The target region for the purity scaling and the $E_{\text{cell}}^{\text{maxE}}$ reweighting has the same kinematic distributions as the SR. For validation of the background model, the $\text{VR-}E_{\text{T}}^{\text{miss}}$ and VR-time were chosen as targets for the purity scaling and $E_{\text{cell}}^{\text{maxE}}$ reweighting procedures.

The application of these processing steps generates the background model which will be used for statistical analysis. The background model consists of five templates of the t_{avg} distribution — one template for each exclusive ρ category. The ranges of each ρ category and the choice of bins for the t_{avg} distribution are listed in Section 9.3.

Chapter 11

Systematic Uncertainties

“If you thought that science was certain - well, that is just an error on your part.”

Richard Feynman

This chapter describes the experimental and theoretical uncertainties which affect the predicted number of signal events for a given signal hypothesis. Systematic uncertainties are classified as “flat” or “shape” uncertainties. Sources of uncertainty that affect only the signal or background normalization are flat uncertainties; similarly, those which affect only the shape of the signal or background distribution are shape uncertainties. The systematic uncertainties are incorporated as nuisance parameters in the profile likelihood fit (cf. Section 12). Section 11.1 describes the uncertainties on the background templates. Section 11.2 describes the uncertainties in the simulated signal events.

In the context of the fit, flat uncertainties can modify the yield of the number of signal or background events (depending on whether the uncertainty affects the signal or the background process). Shape uncertainties, however, can modify the distribution of the variable. In this thesis, the uncertainties on the background model are designed to be shape uncertainties, and those on the signal model(s) are designed to be both flat and/or shape uncertainties. Each systematic uncertainty is built as an envelope around the “nominal” distribution. The two boundaries of this envelope are called the “up-down” variations.

11.1 Background Uncertainties

The background model consists of five independent t_{avg} distributions — one for each exclusive category of ρ . The background model is derived from the CR and then extrapolated to the SR with three processing steps — photon purity scaling, $E_{\text{cell}}^{\text{maxE}}$ reweighting, and residual timing shift. Based on the background model

processing, three systematic uncertainties are constructed. Two of the three systematic uncertainties are based on the photon purity scaling and $E_{\text{cell}}^{\text{max}E}$ reweighting. Another source of uncertainty that accounts for the extrapolation from a low- E_T^{miss} , low-pileup region to a high- E_T^{miss} , high-pileup region is also defined. The three systematic uncertainties on the background templates are described below.

11.1.1 Photon Purity Fraction

The nominal background template is constructed from a combination of the TIGHT-TIGHT and ANTI-TIGHT-TIGHT templates, as shown in Figure 10.1a. Since the photon purity fraction, f_{TT} , changes as a function of the analysis region and ρ category, the purity fraction is rescaled to match the purity expected in the target analysis region and ρ category. Since the events in one analysis region and ρ category pass either the TIGHT-TIGHT or the ANTI-TIGHT-TIGHT selection, a binomial error is assigned to the photon purity fraction. The error on the photon purity fraction is then used to define the systematic up- and down-variations of the photon purity fraction uncertainty.

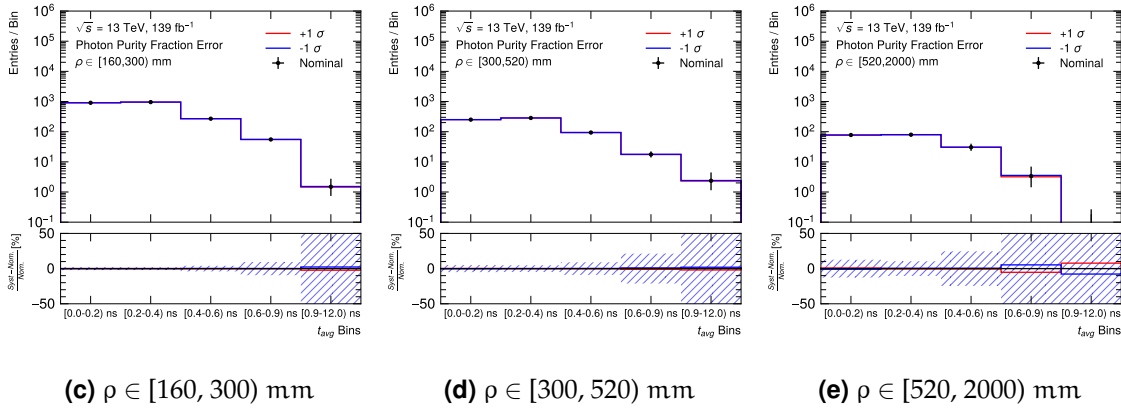
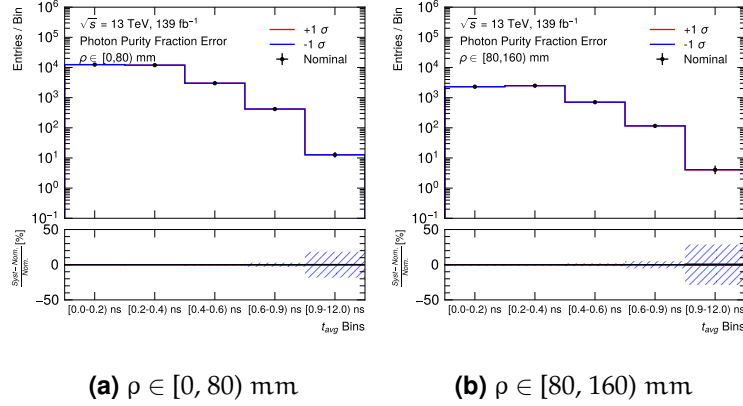


Figure 11.1: Photon purity fraction uncertainty variations for the different ρ categories. The $+1\sigma$ (-1σ) variation is obtained by adding (subtracting) the binomial error to (from) the central value of the photon purity fraction.

11.1.2 $E_{\text{cell}}^{\text{maxE}}$ Reweighting

As described in Section 10.2, the $E_{\text{cell}}^{\text{maxE}}$ distributions of the leading and subleading photons are reweighted to match the expected $E_{\text{cell}}^{\text{maxE}}$ spectra of the photons in the SR. The reweighting is performed exclusively for each ρ category and the reweights are calculated from the ratio of the two-dimensional histogram between the target and the source photons' $E_{\text{cell}}^{\text{maxE}}$ spectra. Therefore, the error on the reweighting is the statistical error of the source and the target histograms.

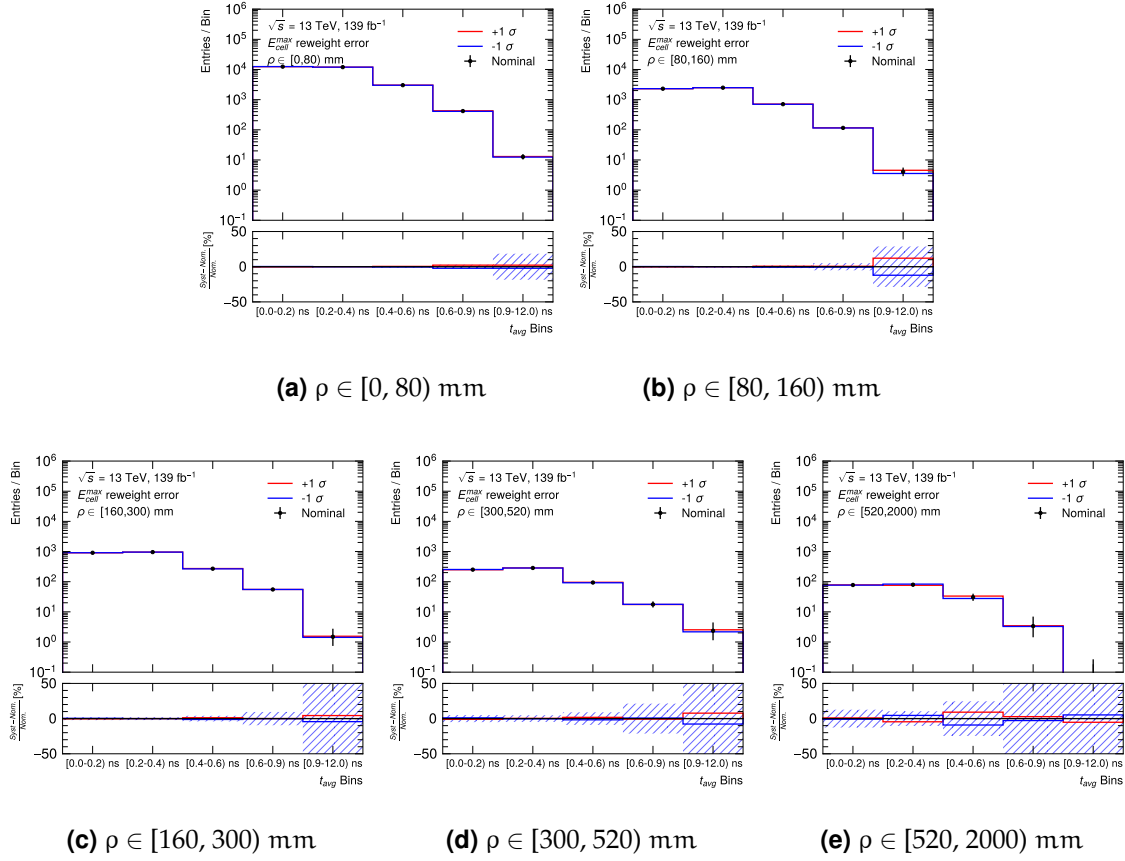


Figure 11.2: $E_{\text{cell}}^{\text{maxE}}$ reweight error uncertainty variations for the different ρ categories. The $+1\sigma$ (-1σ) variation is obtained by adding (subtracting) the $E_{\text{cell}}^{\text{maxE}}$ reweight error to (from) the $E_{\text{cell}}^{\text{maxE}}$ reweight value.

11.1.3 Pileup profile extrapolation

High pileup likely increases the contribution of jets mismeasured as photons and thus degrades the timing measurement of the photon candidates in the high- $E_{\text{T}}^{\text{miss}}$ region. Since the background model is derived from a low- $E_{\text{T}}^{\text{miss}}$ region, to estimate the change in the timing resolution when fit to a high- $E_{\text{T}}^{\text{miss}}$ region a pileup-profile-based uncertainty is defined. The control region events are split into two categories — events with $\langle\mu\rangle < \mu_{\text{cut}}$ and events with $\langle\mu\rangle > \mu_{\text{cut}}$. Although the values of μ_{cut} are dependent on the ρ category, the μ_{cut} values fall in the range of 32–34. The low- and high-pileup selection provides distinct shapes that envelop the inclusive nominal template and provide an uncertainty to extrapolate across regions with

differing pileup conditions.

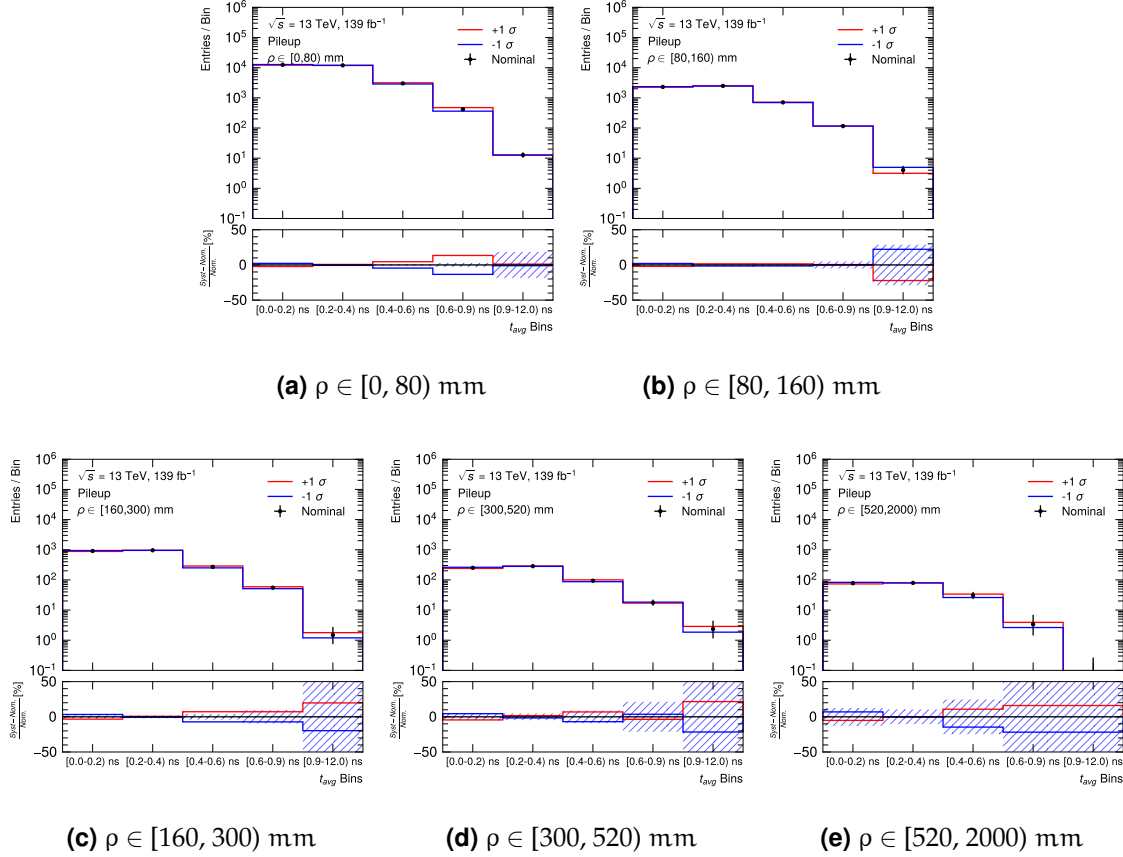


Figure 11.3: Pileup profile uncertainty variations for the different ρ categories. The $+1\sigma$ variation is constructed by requiring the event pileup value is greater than the μ_{cut} for that ρ category. Similarly, the -1σ variation is constructed by requiring the event pileup value to be less than the μ_{cut} for that ρ category.

11.2 Signal Uncertainties

The systematic uncertainties affecting both the shape and normalization of the signal prediction are included in the fit. These arise from experimental conditions, theoretical modeling, or analysis methodologies. The flat uncertainties include the integrated luminosity uncertainty, imperfections due to imperfect detector modeling, and the theoretical uncertainties on the choice of parameters used for the signal MC generation. An uncertainty on the timing smearing procedure (cf.

Section 8.1.4) is implemented as a shape uncertainty on the simulated signal samples. Both the flat and shape uncertainties are correlated across all the ρ categories.

11.2.1 Integrated Luminosity Uncertainty

For Run 2, the integrated luminosity is measured with an error of 1.7% with the methodology described in Ref [152], and using the LUCID-2 subdetector [153].

11.2.2 Detector Uncertainties

The detector uncertainties capture the effects of the experimental limitations related to the detector and the energy scale/resolution of physics object reconstruction. The search follows ATLAS recommendations for the detector uncertainties and includes those related to photon objects, E_T^{miss} , and pileup modeling.

Photon trigger, identification, and isolation efficiency uncertainties account for various sources of disagreement between data and simulation. The photon trigger efficiency is measured using two complementary data-driven methods. The Bootstrap method uses photons triggered by a lower-level or unbiased trigger. The second method uses photons from radiative $Z \rightarrow \ell\ell\gamma$ decays [140]. Photon isolation and identification uncertainties are calculated using an inclusive-photon production, and photons from radiative $Z \rightarrow \ell\ell\gamma$ decays [120].

Electromagnetic energy scale and resolution uncertainties account for various residual differences between data and simulation [121, 122]. These differences include the inter-calibration of the different calorimeter layers, corrections for energy shifts induced by pileup, and corrections to improve the uniformity of the energy response. The uncertainties are determined through a calibration procedure performed with electrons from $Z \rightarrow ee$ events, and validated with electrons from $J/\psi \rightarrow ee$ events and photons from radiation $Z \rightarrow \ell\ell\gamma$ decay.

The uncertainties associated with the measurement of E_T^{miss} account for the E_T^{miss} scale and resolution. The E_T^{miss} scale and resolution uncertainties are calculated from $Z \rightarrow \mu\mu$ events where the expectation is to have little to no E_T^{miss} [135].

Additionally, the pileup distribution of the simulated events is modified to match the profile observed in the data, and an associated pileup reweighting (PRW)

Source of uncertainty	$\tilde{\chi}_1^0$ (135 GeV, 2 ns), H + $\tilde{G}$	
	+1 σ [%]	−1 σ [%]
Electromagnetic energy scale	1.04	−1.17
Electromagnetic energy resolution	0.03	0.14
Photon trigger efficiency	0.49	−0.49
Photon identification efficiency	1.55	−1.54
Photon isolation efficiency	1.46	−1.45
E_T^{miss} scale	−0.51	0.66
E_T^{miss} resolution	0.77	0.77
Pileup reweighting	−0.39	0.68
Total	2.63	2.75

Table 11.1: Breakdown of the impact of the detector uncertainties on the $\tilde{\chi}_1^0$ (135 GeV, 2 ns), H + $\tilde{G}$ sample.

uncertainty is assigned which accounts for the discrepancy in the pileup distribution between data and simulation.

The breakdown of the impact of the detector systematic uncertainties for the $\tilde{\chi}_1^0$ (135 GeV, 2 ns), H + $\tilde{G}$ signal sample is shown in Table 11.1.

11.2.3 Theory Uncertainties

The theoretical uncertainties on the choice of the strong coupling constant (α_S), the renormalization (μ_R), and the factorization (μ_F) scale variations, as well as the choice of parton distribution functions (PDFs), are added to the signal prediction. The uncertainties on each of these theoretical parameters are determined by varying their respective value and measuring the impact on the signal. The impact of these theoretical uncertainties is combined and evaluated as a change in the signal yield, i.e., a flat uncertainty. The impact of the individual theoretical uncertainties, on two different signal points, is shown in Table 11.2.

Source of uncertainty	$\tilde{\chi}_1^0$ (225 GeV, 2 ns), H + $\tilde{G}$ $\pm 1\sigma$ [%]	$\tilde{\chi}_1^0$ (225 GeV, 2 ns), Z + $\tilde{G}$ $\pm 1\sigma$ [%]
α_S	0.1	0.1
μ_R, μ_F	12.6	12.6
PDF replicas	0.4	0.4
Total	12.6	12.6

Table 11.2: Breakdown of the impact of theoretical uncertainties on two signal models — $\tilde{\chi}_1^0$ (225 GeV, 2 ns) with H + $\tilde{G}$ and Z + $\tilde{G}$ decay modes.

11.2.4 Timing Resolution Uncertainty

The photon timing in simulation is smeared to match the timing resolution observed in data (cf. Section 8.1.4). The timing resolution uncertainty is calculated by implementing additional smearing to the timing distribution in simulation. The additional smearing accounts for the residual differences in the timing resolution between data and MC. The calculation of the timing resolution uncertainty follows the procedure used in previous non-pointing photon analysis [76]. Figure 11.4 shows the distribution of leading and the subleading photon timing distributions for the $\tilde{\chi}_1^0$ (135 GeV, 2 ns), H + $\tilde{G}$ signal sample. As evident in the figure, the smeared variations deviate less than 5% from the nominal (unsmeared) distribution. The impact of applying the smearing on the shape of the t_{avg} distribution is within

the statistical uncertainty of the nominal t_{avg} distribution. Since the inclusion of the timing smearing uncertainty has a negligible impact on the shape the timing smearing uncertainty is removed from the fit.

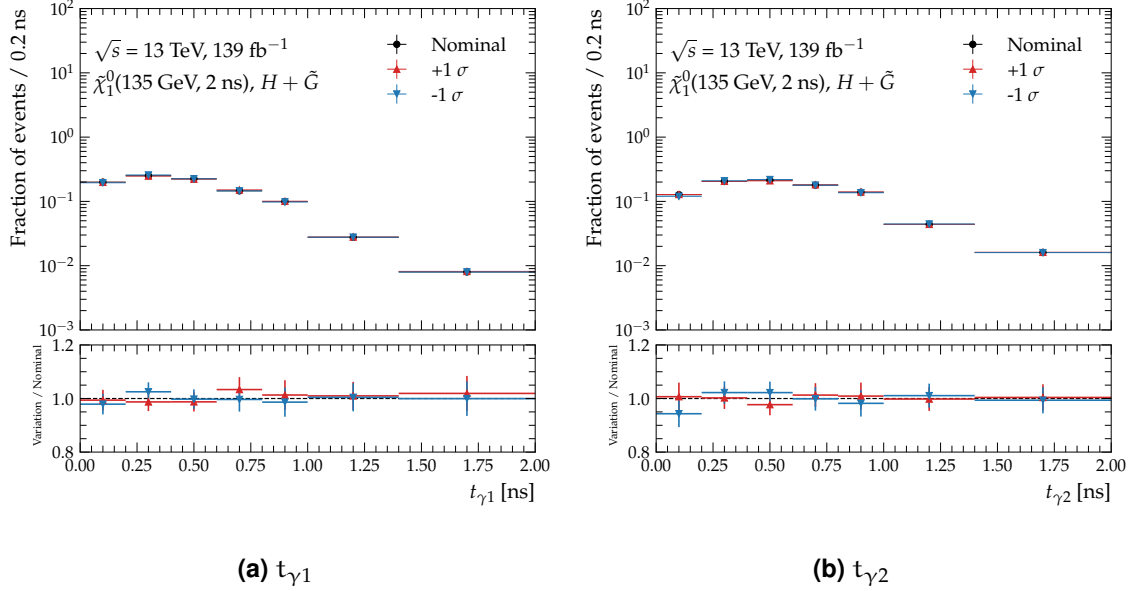


Figure 11.4: Timing distributions of the lead and sublead photons for the $\tilde{\chi}_1^0$ (135 GeV, 2 ns) signal sample. The top panel shows the $\pm 1\sigma$ variations of the timing smearing uncertainty overlaid with the nominal distribution that doesn't have any additional smearing. The bottom panel shows the ratio of the systematic variation with respect to the nominal. The smeared variations are within 5% of the nominal values.

An additional source of uncertainty, although not a systematic uncertainty, arises from the limited statistics of the background and the signal models. The effect of limited statistics is described by adding Poisson constraints for each bin and for each region of the ρ category of the t_{avg} distribution. These constraints are called "gammas" and are implemented in the fit in the same manner as the other systematic uncertainties.

This chapter described the types and sources of uncertainties on the background and the signal models. The uncertainties on the background model are derived from the three processing steps — photon purity scaling, $E_{\text{cell}}^{\text{maxE}}$ reweighting, and pileup profile extrapolation — to extrapolate the CR t_{avg} distribution to the expected background distribution in the SR. The uncertainties on the background are

implemented as shape uncertainties. There are several sources of uncertainty on the signal model. These uncertainties arise from experimental conditions, theoretical modeling, and analysis methodology. The uncertainties on the signal model are implemented as both shape and flat uncertainties. For the background model, the uncertainty pileup profile extrapolation provides the largest variations in the shape of the background t_{avg} distribution. Similarly, for the signal model, the theory uncertainties provide the largest variation in the signal yield. The shape uncertainties on the signal model do not vary the shape of the nominal distribution significantly, i.e. more than 5% from the nominal shape.

Chapter 12

Statistical Analysis

Extraordinary claims require
extraordinary evidence

Carl Sagan

This chapter describes the statistical concepts, tools, and methods used in high-energy physics and then their application to this analysis. Statistical tools are vital for all analysis in particle physics designed to search for rare processes or extract small signals from large data sets. These tools provide quantitative methods to perform hypothesis testing and to set exclusion bound(s) on a signal process in absence of a discovery. Section 12.1 describes the common statistical concepts, and Section 12.2 describes the statistical analysis framework employed for the search. Section 12.3 describes the validation of the fit framework and the background model.

12.1 Statistical Analysis Concepts

12.1.1 Hypothesis Testing

In particle physics, the discovery or exclusion of a model is performed through a statistical test called *hypothesis testing*. Two hypotheses, a null hypothesis (H_0) describes the expectation without the presence of a signal, and an alternate hypothesis (H_1) describes the expectation with the presence of a signal, are tested. In particle physics, H_0 is referred to as the *background-only* hypothesis, and H_1 is referred to as the *signal-plus-background* hypothesis. The level of compatibility of the observed data with each of the two hypotheses is used to make a statement about the validity of the model. For this search, the background-only hypothesis will be the photon candidates which are mismeasured objects such as jets. The signal-plus-background hypothesis will be the photon candidates which are produced from the decay of the long-lived $\tilde{\chi}_1^0$.

The two hypotheses can be generalized by introducing a parameter, μ , which will be the *signal strength*. This parameter is the ratio of the observed cross section to the predicted cross section. Since the number of events for a given process is proportional to its production cross section, the signal strength can be expressed as

$$\mu = \frac{\sigma_{\text{observed}}}{\sigma_{\text{expected}}} \approx \frac{N_{\text{observed}}}{N_{\text{expected}}} \quad (12.1)$$

Where N_{observed} (N_{expected}) are the number of observed (expected) events and σ_{observed} (σ_{expected}) is the observed (expected) cross section. In the case $\mu = 0$, one recovers the background-only hypothesis, and when $\mu = 1$ one recovers the signal-plus-background hypothesis.

The compatibility of the observed data with a given hypothesis is quantified with a test statistic. From the test statistic, a *p-value*, p_μ , can be computed which provides the probability that the observed data are described using a model with signal strength μ . For e.g., the p_0 -value quantifies the agreement of the observed data under the background-only hypothesis. The p-value can be converted into a corresponding Gaussian significance, Z , defined as the number of standard deviations that correspond to an upper-tail probability p_μ for a Gaussian-distributed variable. In particle physics, the threshold to refute a hypothesis is chosen to correspond to a p-value of less than 5% ($Z = 1.64$). Similarly, if the background hypothesis has a $p_0 = 1.3 \times 10^{-3}$, an equivalent significance of $Z = 3$, the background-only hypothesis can be rejected and evidence of the signal process is announced. A discovery for the signal-plus-background hypothesis is stated when $p_0 = 2.87 \times 10^{-7}$ which is an equivalent significance of $Z = 5$. Figure 12.1 illustrates the significance thresholds for claim, evidence, and discovery.

12.1.2 Can one event be a discovery?

Suppose one designs an experiment where fewer than 2.87×10^{-7} background events are expected. If one observes one event, does it imply a 5σ discovery?

The answer depends on the confidence of the background hypothesis. Is it possible that contributions to the background are missing or mismeasured? What if one is looking for a "bump" anywhere in the spectrum? To prevent accidental discoveries in experiments that aim to discover new phenomena by performing

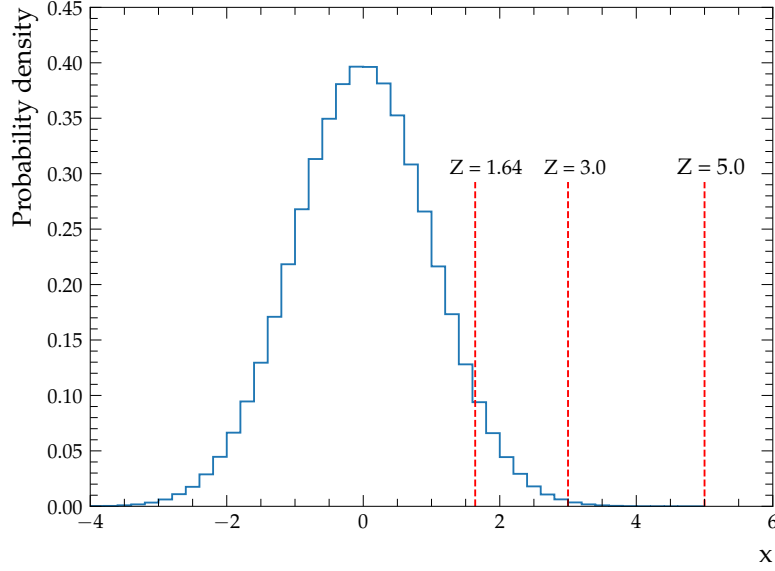


Figure 12.1: Significance thresholds chosen as convention for a claim ($Z = 1.64$), evidence ($Z = 3.0$), and discovery ($Z = 5.0$) of a new physics process

a search over a large space of parameters, a "*look-elsewhere-effect*", or a trials-factor [154] calculation is performed. To assess the significance of a local deviation from the background hypothesis in terms of p-value, one needs to take into account the probability of such a deviation occurring anywhere within the search range.

The "brute-force" solution to this problem is to generate a Monte Carlo simulation of the data under the background-only hypothesis and for each data set, fitting a peak of unknown position and recording its significance. However, for a discovery which requires $p_0 \approx 2.87 \times 10^{-7}$, generating and fitting very large number of experiments ($\mathcal{O}(10^7)$) may be computationally expensive. In contrast, if the position of the peak is fixed, then one can modify the local p-value to the correct "global" value using a relatively simple calculation. Suppose a test statistic, q_0 , is defined so that larger values indicate increasing disagreement with data, and is observed to have a value u . Also, suppose the peak position is only defined under the signal process. Then, an approximation for the global p-value will be

$$p_{\text{global}} \approx p_{\text{local}} + \langle N_u \rangle \quad (12.2)$$

Where $\langle N_u \rangle$ is the mean number of up crossings of the statistic q_0 above the level u [154].

The value of $\langle N_u \rangle$ can be estimated from the number of upcrossings $\langle N_{u_0} \rangle$ above some much lower value, u_0 , using the relation [155]

$$\langle N_u \rangle \approx \langle N_{u_0} \rangle e^{-(u-u_0)/2} \quad (12.3)$$

Thus, by choosing a sufficiently low value of u_0 , the value of $\langle N_u \rangle$ can be estimated by simulating only a very small number of experiments.

12.1.3 No signal, but exclusion!

An important example of a statistical test arises in the search for a new signal process. Since the signal strength, μ is proportional to the cross section, a statistical test may be performed for hypothetical values of μ . The statistical test could be performed by computing the p-value, p_μ , for all values of μ ; the values of μ not rejected in a test of size α , i.e., where one does not find $p_\mu \leq \alpha$, constitute a confidence interval with confidence level $1 - \alpha$.

In some regions in the parameter space of the signal model, the predictions for data are almost indistinguishable from those of the background-only model. This corresponds to the case where μ is very small. Thus, it would be preferred that if the sensitivity to a model is very little, then the model should not be excluded. The exclusion of models to which one has little or no sensitivity occurs if the data fluctuate very low relative to the expectation of the background-only hypothesis. One way to mitigate the problem of excluding models to which one is not sensitive is the CL_s method [156, 157]. The procedure is based on a statistic called CL_s which is defined as

$$CL_s = \frac{p_\mu}{1 - p_0} \quad (12.4)$$

Where, p_0 is the p-value of the background-only hypothesis. In the usual formulation of the method both p_μ and p_0 are defined using a single-sided test statistic.

A point in the model's parameter space is excluded if one finds $CL_s \leq \alpha$. The CL_s statistic provides a more stringent than the usual requirement $p_\mu \leq \alpha$. In

particle physics, the common convention is if $CL_s < 0.05$ then the parameter-space point is excluded at 95% confidence level.

12.1.4 Likelihood Function and Profile Likelihood Ratio

The likelihood function describes the probability of a particular model to describe the observed data. Consider a single-bin experiment where the expected number of events can be expressed as

$$n_{\text{expected}} = \mu \cdot s + b \quad (12.5)$$

Where, μ is the signal strength, s (b) is the number of predicted signal (background) events. The expectation, n_{expected} , can be compared to the observed number of events, n_{observed} , in data. Assuming the data can be described with a Poisson distribution, the likelihood for the data to be produced by the model is given by

$$\mathcal{L}(\mu) = \frac{(\mu \cdot s + b)^{n_{\text{observed}}}}{n_{\text{observed}}!} e^{-(\mu \cdot s + b)} \quad (12.6)$$

The statistical and systematic uncertainties on the signal and background prediction are incorporated as *Nuisance Parameters* (NPs), θ , into the likelihood function. A variation in an NP produces a change in the predicted number of events, $s(\theta)$ and $b(\theta)$. The NPs are characterized by a probability distribution function (pdf) which encodes information about the best estimate and width of the nuisance parameter. The pdfs for each uncertainty are determined beforehand by auxiliary measurements. The most common parametrization of the NP is through a Gaussian distribution. The NPs are included in the likelihood function as multiplicative terms to the Poisson distribution. Building on our single-bin experiment example, if we have an experimental observable with i bins the likelihood function, with the inclusion of the NP terms, can be written as:

$$\mathcal{L}(\mu, \theta) = \prod_i \mathcal{P}(n_{\text{observed}}^i | n_{\text{expected}}^i) \prod_k \mathcal{G}(\tilde{\theta}_s^k | \theta_s^k, \sigma_s^k) \prod_l \mathcal{G}(\tilde{\theta}_b^l | \theta_b^l, \sigma_b^l) \quad (12.7)$$

Where, $\mathcal{P}$ ($\mathcal{G}$) is the shorthand for Poisson (Gaussian) distribution, $\tilde{\theta}$ is the

measured value of the NP for the best estimate value θ and the width σ . The likelihood function is a product of the signal and background uncertainties, indexed by k and l , respectively.

The nuisance parameters are redefined to be centered about zero with a width of one to compare the impact of the nuisance parameters pre- and post-fit. For a Gaussian distribution, the rescaling of the parameter can be performed as:

$$\theta' = \frac{\theta - \hat{\theta}}{\sigma} \quad (12.8)$$

The likelihood function can be globally maximized, where both the signal strength and the nuisance parameters are fitted. The unconditional maximum likelihood is denoted by $\mathcal{L}(\hat{\mu}, \hat{\theta})$. The likelihood can also be maximized for a fixed value of μ , and the resulting conditional maximum likelihood is denoted by $\mathcal{L}(\mu, \hat{\theta})$. The ratio of both defines the *profile likelihood ratio*, $\lambda(\mu)$, which is the test statistic of choice for most ATLAS searches.

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad (12.9)$$

The profile likelihood ratio is in the range $0 < \lambda < 1$, with values close to one implying good agreement between data and the best fit. Another common test statistic is $q_\mu = -2 \ln \lambda(\mu)$. The profile likelihood ratio can be used to calculate p-value and also compute the CL_s "confidence limits" [158].

12.2 Fit Implementation

The statistical analysis is performed using TREXFITTER [159], a profile likelihood fit framework employed by numerous ATLAS analyses. As discussed earlier, the fit is performed on the average timing distribution sliced into five vertexing categories. The background normalization in each ρ category is kept free-floating. The NPs which correspond to uncertainties associated with the signal and background templates are assigned Gaussian constraints. The fit procedure was designed with the SR timing and vertexing distributions in data kept blind, i.e. the development of the systematic uncertainties, or the fit procedure was not biased by the possible observations in the SR.

12.3 Fit Validation

Fit validation requires the validation of both the fit framework and the background model. The fit framework is validated by conducting the spurious signal, and signal injection tests, and performing fit on pseudo-datasets constructed from the VRs. The background modeling is validated by performing the fit on the VRs.

12.3.1 Validation of Fit Procedure

The fit framework is tested and validated by performing fit on pseudo-datasets. These pseudo-datasets are generated with the background-only hypothesis. Each pseudo-dataset is generated from the CR background template. Before generating the dataset, the photon purity fraction is rescaled to match the expected purity fraction in the target analysis region. Additionally, the $E_{\text{cell}}^{\text{maxE}}$ reweighting is also performed to match the $E_{\text{cell}}^{\text{maxE}}$ spectra of the source photons to the observed spectra in the target analysis region.

The spurious signal test checks that the fit does not extract a large non-zero signal strength if none exists in the observed data. The spurious signal test is performed on 1000 pseudo-datasets generated from the expected background t_{avg} distribution in the VR-time analysis region. For the spurious signal test, a signal-plus-background fit is performed for each pseudo-dataset and the fitted value of the signal strength and its error are recorded. The signal model chosen for the spurious signal test is the $\tilde{\chi}_1^0$ (225 GeV, 2 ns), $H + \tilde{G}$ simulated sample. The distribution of the fitted value of the signal strengths is shown in Figure 12.2a. The distribution of the fitted μ is bound near a very small, negative value — $\mu \approx -0.05$, motivated by the smallest possible signal which will keep the bin content in the highest timing bin greater than or equal to zero.

The signal injection test checks that the fit extracts the correct signal strength when a signal of known strength is added or "*injected*" to the observed data. The background model for this test was generated from the CR background template called the *Asimov* dataset¹. A signal of known strength is added to the background distribution, and a signal-plus-background fit is performed. Figure 12.2b shows the

¹An Asimov dataset is generated for a particular set of model parameters such that the maximum likelihood best-fit value of all those parameters are equal to their generated values.

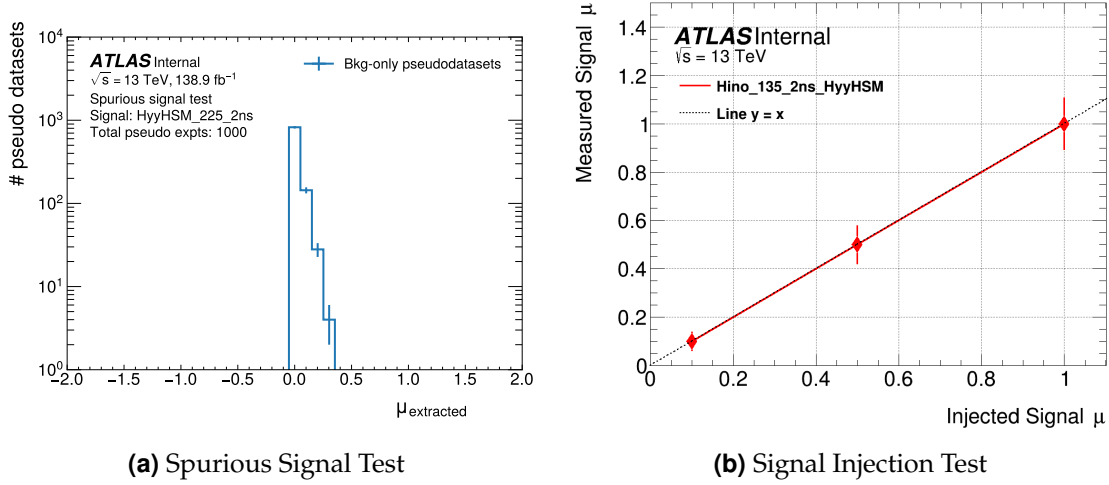


Figure 12.2: Results of the spurious signal and the signal injection tests. The spurious signal test is performed on 1000 pseudo-datasets and the $\tilde{\chi}_1^0$ (225 GeV, 2 ns) signal sample. The signal injection test is performed with an Asimov dataset with different signal strengths for the $\tilde{\chi}_1^0$ (135 GeV, 2 ns) signal sample.

results of the extracted signal strength as a function of the injected signal strength. The signal injection test was performed on the $\tilde{\chi}_1^0$ (135 GeV, 2 ns), $H + \tilde{G}$ signal sample. As evident from the figure, the appropriate signal strength is extracted from the fit, and the extracted and injected signal strengths are in good agreement. The linear relationship between the extracted and the injected signal strength implies the background model is able to successfully recover injected signal events.

12.3.2 Validation of Background Model

The background model is validated by performing background-only, and signal-plus-background fits in the various VRs. The analysis is categorized into two major — a mid- E_T^{miss} and a high- E_T^{miss} — VRs (cf. Section 9.2). The mid- E_T^{miss} validation region is further split into two regions based on the sign of the two photon times. A $(\text{VR}-E_T^{\text{miss}})^{t>0}$ region which consists of pospos photons, and a $(\text{VR}-E_T^{\text{miss}})^{t<0}$ region which consists of negneg photons. Thus, the background model is tested with data from three validation regions.

A background-only fit is performed in each of the validation regions. The t_{avg} distribution across all ρ categories shows good agreement between VR-data and

the post-fit background. The t_{avg} background and data distributions for fits to the VR-time dataset are shown in Figure 12.3. Good agreement is observed between the background model and the data in the three VRs. Additionally, no systematic deviations in the timing shapes are observed, further reinforcing the validity of the background modeling.

The pull distributions of the background systematic uncertainties are shown in Figure 12.4. While there is some trend in the pull distributions in the VR-time and VR- E_T^{miss} region fits, the overall behavior of the pull distributions displays no strong bias associated with any systematic uncertainty.

Table 12.1 shows the p_0 -values for the background-only fit to the three VRs. The p_0 -values are consistent with the background-only hypothesis. Additionally, a spurious signal significance, defined as the ratio of the fitted signal strength to its uncertainty is also listed in the table. The maximum spurious signal is roughly 1. The background-only fits and spurious signal tests provide confidence in the background model and also highlight the fact that the VR does not contain any features which can mimic signal.

	HyyHSM		ZeeZSM	
	p_0 -value	Spurious Signal Significance	p_0 -value	Spurious Signal Significance
VR-time	0.65	−0.41	0.71	−0.55
$(\text{VR-}E_T^{\text{miss}})^{t>0}$	0.37	0.34	0.19	0.87
$(\text{VR-}E_T^{\text{miss}})^{t<0}$	0.14	1.09	0.22	0.76

Table 12.1: Distribution of p_0 -values and spurious signal significance for VR fits for the $\tilde{\chi}_1^0$ (135 GeV, 2 ns) signal sample for the $H + \tilde{G}$ and $Z + \tilde{G}$ decay modes.

Number of Events	VR-time	$(\text{VR}-E_T^{\text{miss}})^{t>0}$	$(\text{VR}-E_T^{\text{miss}})^{t<0}$
Observed	5	14	18
Expected	10.7 ± 2.2	17.3 ± 2.7	18.4 ± 2.8

Table 12.2: Expected and observed number of background events in the analysis VRs.

Validation of Discovery Region

The discovery region is designed to provide a model-independent interpretation. As described in Section 9.2, the discovery region is defined by the ρ -inclusive t_{avg} distribution. The discovery region analysis consists of providing the expected number of background events in the highest t_{avg} bin, $t_{\text{avg}} \in [0.9, 12)$ ns. Table 12.2 provides the expected number of background events for the three VRs. The expected number of events is in good agreement with the observation, and the observed number of events is within 2σ of the expectation.

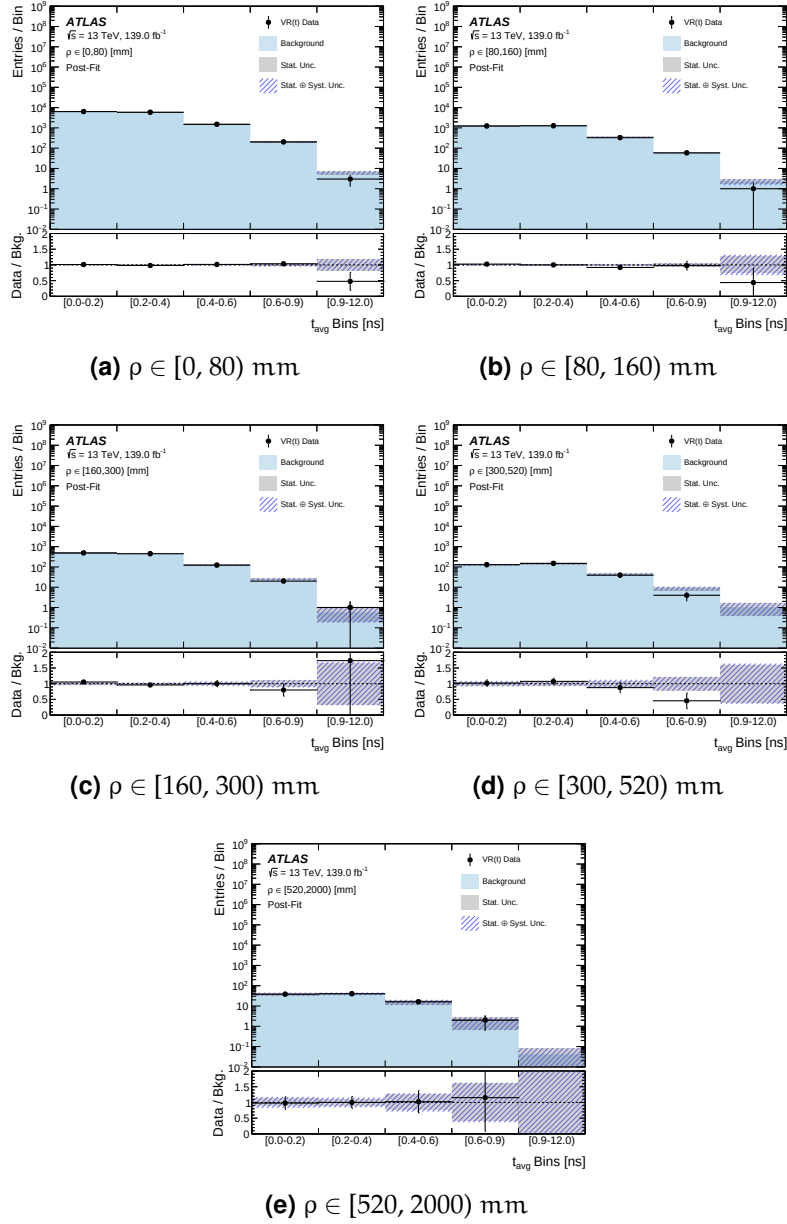


Figure 12.3: Post-fit t_{avg} distributions for background-only fits to the VR-time data. The top panel shows the t_{avg} distributions for the background model and the VR-time region. The grey band represents the statistical uncertainty of the background model, and the blue hatched band represents the statistical and systematic uncertainties added in the quadrature. The bottom panel shows the ratio of the VR-time distribution to the background distribution. The data and background t_{avg} distributions for each ρ category are in good agreement.

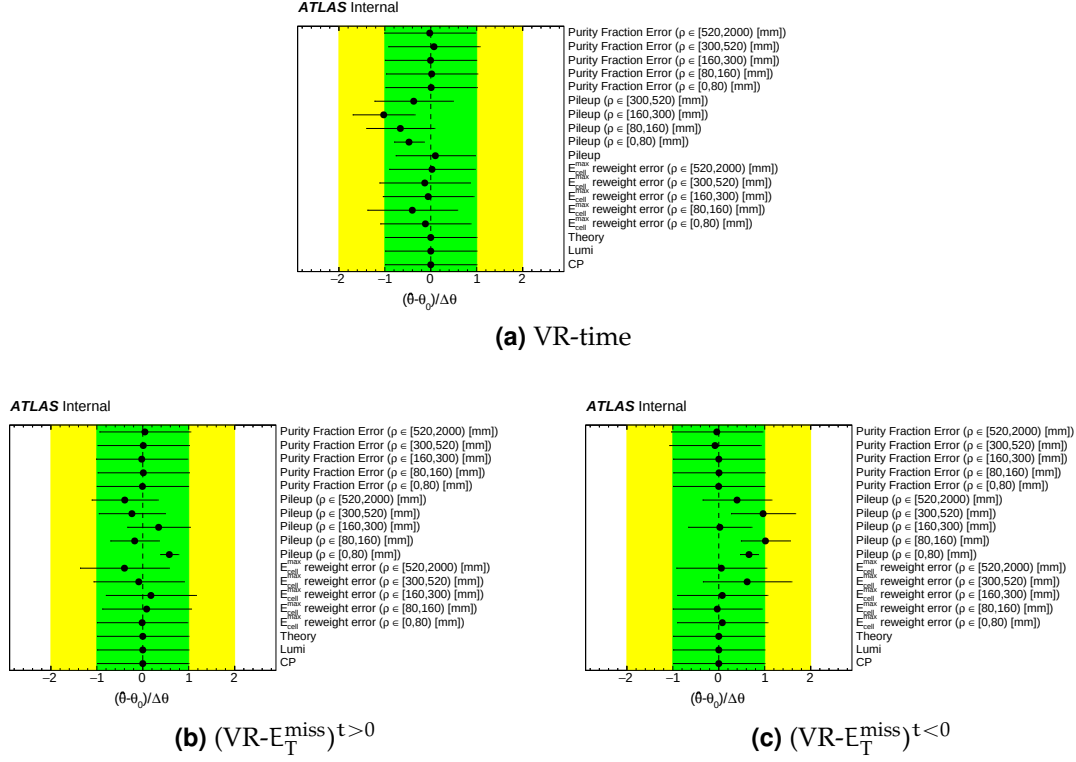


Figure 12.4: Background-only fit pull distributions of the background systematic uncertainties in the three VRs. Each plot shows the post-fit pull distributions of the systematic uncertainties on the signal and background models. The background model uncertainties — $E_{\text{cell}}^{\text{max}E}$ reweighting, photon purity rescaling, and pileup profile extrapolation — are decorrelated across the five ρ categories. For the signal model, the theoretical, luminosity, and detector uncertainties are correlated across the ρ categories. The pull for a systematic uncertainty can be a post-fit shift in the central value, $\hat{\theta}$, or a constraint in the 1σ variation, $\Delta\theta$, or both. The dashed vertical line at $y = 0$ represents the pre-fit central value of the systematic uncertainty, and the green (yellow) band represents the $+1$ ($+2$) σ variation.

Chapter 13

Results and Interpretation

Meaning lies as much
in the mind of the reader
as in the Haiku.

*Douglas Hofstadter
Gödel, Escher, Bach: An Eternal
Golden Braid*

This chapter describes the results of the search performed on the unblinded signal region data. No significant excess over the background expectation is observed; therefore, 95% C.L. upper limits are set on the $\tilde{\chi}_1^0$ production cross section, $\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0)$. Limits are presented as a function of three parameters of the signal grid, the $\tilde{\chi}_1^0$ mass and lifetime, under the assumption of 100% branching ratio ($\mathcal{B}$) to either Higgs or Z bosons, as well as the $\mathcal{B}$ of the $\tilde{\chi}_1^0$ to the SM Higgs/Z boson for specific mass and lifetime hypotheses. Limits as a function of the $\tilde{\chi}_1^0$ decay modes can also be computed by combining samples with both Higgs and Z boson decays of the $\tilde{\chi}_1^0$, as well as the decay of the other $\tilde{\chi}_1^0$ which does not produce a displaced diphoton vertex. For the model-independent results, the observed number of events in the unblinded signal region is also presented.

13.1 Unblinded Signal Region Results

Once the background estimation and the fit procedure were validated, the SR timing and vertexing distributions were unblinded. First, a background-only fit was performed on the unblinded data to assess the compatibility of the observed data under the background-only hypothesis. Figure 13.1 shows the t_{avg} distribution for the post-fit background and the unblinded SR data. Overlaid on the two t_{avg} distributions are the timing distributions for various signal hypotheses.

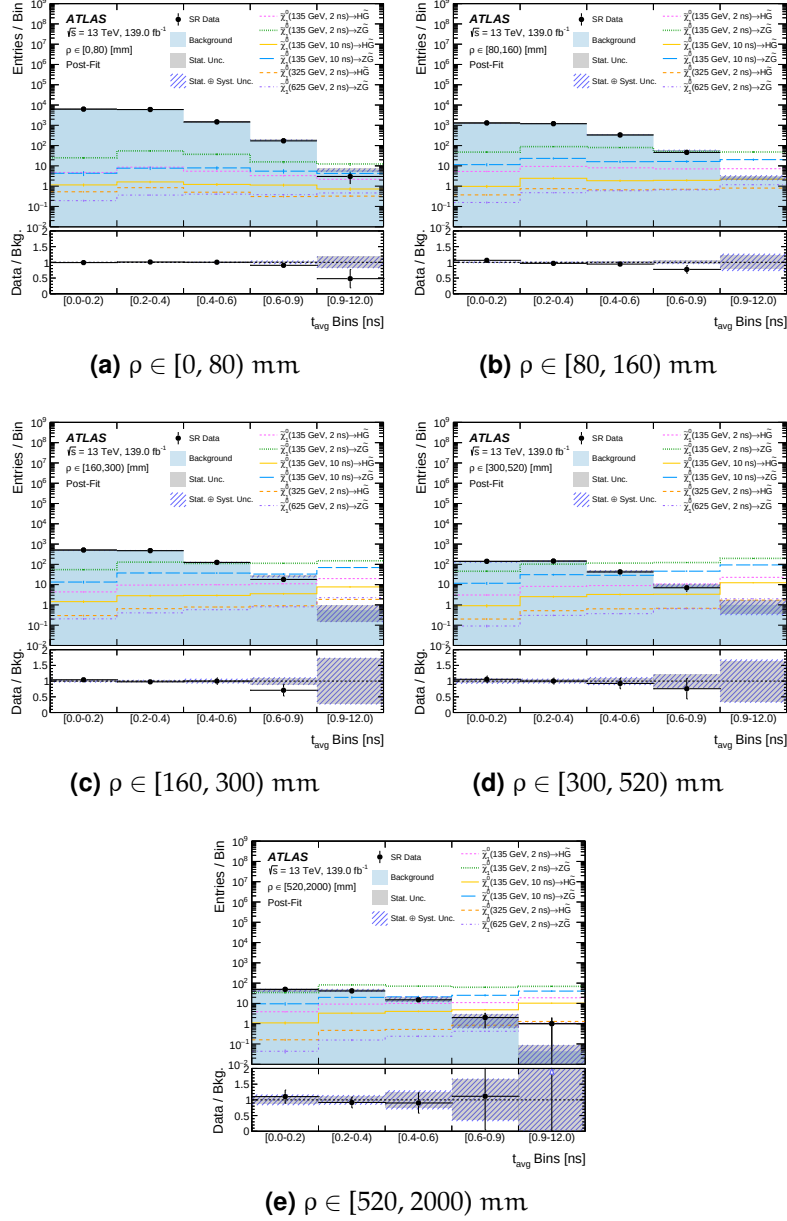


Figure 13.1: Average timing distributions for SR data and the estimated background as determined by the background-only fit, in each of the five exclusive ρ categories. For comparison, the expected timing shapes for a few different signal models are superimposed, with each model labeled by the values of the $\tilde{\chi}_1^0$ mass and lifetime, as well as decay mode. To provide some indication of the variations in signal yield and shape, three signal models are shown for each of the $\tilde{\chi}_1^0$ decay modes, namely $\tilde{\chi}_1^0 \rightarrow H + \tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}$. The models shown include a rather low $\tilde{\chi}_1^0$ mass value of 135 GeV for lifetimes of either 2 ns or 10 ns and a higher $\tilde{\chi}_1^0$ mass value which is near the 95% C.L. exclusion limit for each decay mode for a lifetime of 2 ns. Each signal model is shown with the signal normalization corresponding to a branching ratio value of unity for the decay mode in question.

The post-fit background and the observed data are in good agreement; although the observed t_{avg} distribution is narrower than the expectation, the post-fit background can describe the observation. The pull distributions of the background systematic uncertainties are shown in Figure 13.2. As evident from the distribution, the pileup profile uncertainty is significantly pulled, with a consistent trend of the pull in the -1σ direction. As shown in Figure 11.3, the pileup profile uncertainty variations provide the required deviation from the nominal t_{avg} distribution to describe the narrower than expected t_{avg} distribution of the SR data. The origin of the slight shape difference between the background templates and the observed data is not completely clear since the timing resolutions do not exhibit large variations across the variables that define the SR (Appendix B.4). One possible explanation could be the purity scaling may not fully capture the evolution of the photon purity fraction across the analysis regions.

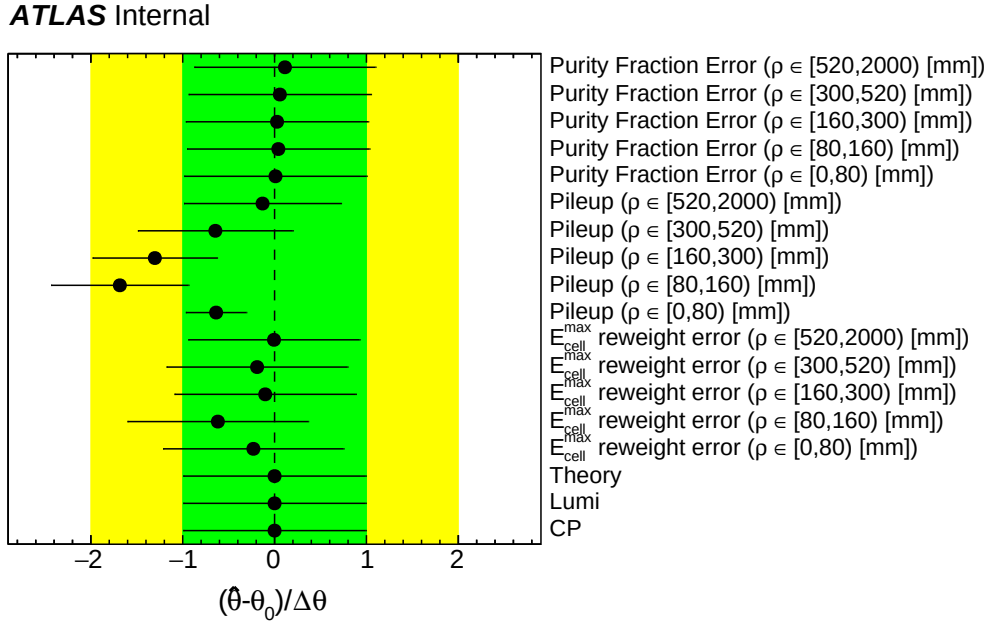


Figure 13.2: Pull distributions of the background systematic uncertainties for a background-only fit to the SR data.

Another striking feature of the SR t_{avg} distribution is the single-bin deviation in the highest ρ category and in the timing bin $t_{\text{avg}} \in [0.9, 12.0)$ ns. This event was studied in further detail to understand the event characteristics. The event

was recorded in Run 359593 and has event number 761048468. The event has $\rho = 560$ mm, and the photon times are $t_{\gamma 1} = 5.82$ ns (leading photon), $t_{\gamma 2} = 0.45$ ns (subleading photon).

The leading photon is most likely a jet; the object corresponding to the leading photon was reconstructed as both the photon and a misidentified jet. Since the overlap removal (cf. Section 6.2.6) prioritizes photons over jets, the object was reconstructed as a photon candidate. The photon-jet ambiguity, as well as the fact that the candidate does not pass the Tight photon identification also suggests the leading photon candidate is most likely a jet. Additionally, the timing value of 5.82 ns is also consistent with the timing of the satellite collision. The timing measurements of the neighboring cells in the same EM calorimeter cluster have similar values, suggesting that the timing measurement of 5.82 ns is relatively accurate. The subleading photon is measured with a pointing value of $z_{\gamma 2} = -11.6$ mm. The sublead photon candidate passes the Tight photon identification and does not have ambiguity with any other reconstructed object. The pointing and timing value of the subleading photon are consistent with the production of a prompt photon and is not compatible with the photon candidate being produced in a satellite collision.

The single-bin event is also incompatible with the signal model since the two photons produced in the same vertex would have correlated timing values. Therefore, if this event were a signal event, both the photon times would be delayed, which is not the case for the photon candidates in the single-bin event. The single-bin event is more compatible with a satellite collision overlaid with a prompt collision.

The background estimation, derived from the CR, includes events produced in satellite collisions. An estimated number of satellite-collision events is obtained by counting the number of such events in the CR and scaling it by the fraction of events in the SR. Note, the estimation of the satellite-collision events assumes that the prevalence of these events is uncorrelated with the event kinematics. If both the photon candidates have $4 < t_{\gamma} < 6.5$ ns, then the event is considered to be produced in a satellite collision. The estimation of the rate of satellite collisions predicts 0.5 ± 0.3 events in the SR; 1 such event is observed. Although this estimation is based on statistical extrapolation, it demonstrates that the number of satellite

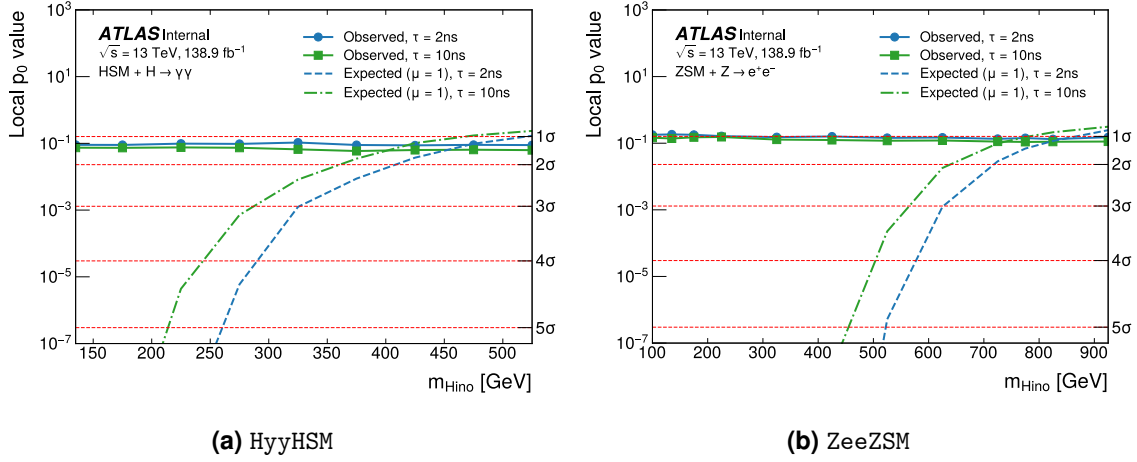


Figure 13.3: Local p_0 -values for the HyyHSM and ZeeZSM signal models as a function of the $\tilde{\chi}_1^0$ mass and lifetime.

collisions observed in the SR is comparable to the expected value.

The signal-plus-background fit was performed after the background-only fits. The p_0 -values and their corresponding significances are also calculated for several signal hypotheses. The distribution of the p_0 -values for the HyyHSM and ZeeZSM signal models generated at 2 ns and 10 ns $\tilde{\chi}_1^0$ lifetimes are shown in Figure 13.3. As evident in the figure, the p_0 -values are relatively flat for both decay modes. Since the timing distributions for the various HyyHSM and ZeeZSM signal models are similar (cf. Figure 13.1), the p_0 -values the two decay modes are expected to have similar values.

13.2 Limits and Exclusion

As no significant excess over the background expectation is observed, 95% C.L. upper limits on the $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ production cross section are calculated using the CL_s technique [156, 157] under the asymptotic approximation [158]. The exclusion limits are set as a function of the mass, lifetime, and branch ratio of the $\tilde{\chi}_1^0$.

Figure 13.4 shows the upper limit on the $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ for the HyyHSM and ZeeZSM decay modes as a function of the $\tilde{\chi}_1^0$ masses. The colored band depicts the observed, expected upper limits along with the $\pm 1\sigma$ uncertainty on the expected

upper limit. The different colored bands show the upper limit on the cross section for the different $\tilde{\chi}_1^0$ lifetimes. The theoretical prediction on the production cross section is also shown in the figure. As expected, signal models with higher $\tilde{\chi}_1^0$ masses have a lower cross section. The masses below the theoretical curve are considered *excluded* at a 95% C.L.

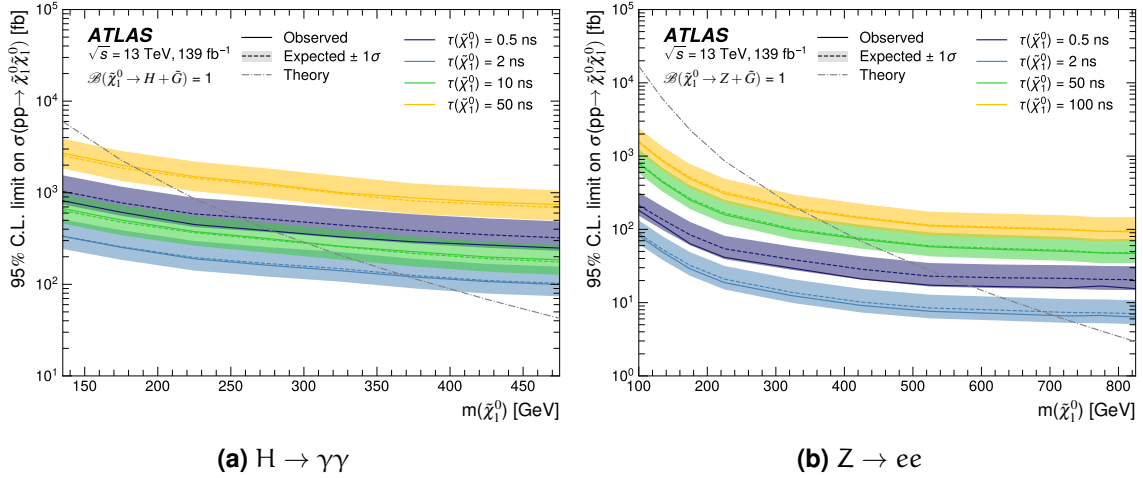


Figure 13.4: 95 % C.L. limit on $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ mass for the different decay modes $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G}) = 1$ and $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1$. The different colored bands represent the upper limits for different $\tilde{\chi}_1^0$ lifetimes. Included are the theoretical expectations for each mass hypothesis, calculated from a GMSB SUSY model that assumes nearly degenerate $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^0$.

Figure 13.5 shows the upper limit on the $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ for the HyyHSM and ZeeZSM decay modes as a function of the $\tilde{\chi}_1^0$ lifetimes. Analogous to Figure 13.4, the colored band depicts the observed, expected upper limits along with the $\pm 1\sigma$ uncertainty on the expected upper limit. The different colored bands show the upper limit on the cross section for the different $\tilde{\chi}_1^0$ masses. For signal models with low $\tilde{\chi}_1^0$ lifetimes, the distribution of the t_{avg} distribution of the signal and background events is hard to distinguish. For the high $\tilde{\chi}_1^0$ lifetimes, the signal acceptance is low since a higher lifetime implies the $\tilde{\chi}_1^0$ has a higher chance to decay outside the detector. The strongest exclusion limits are obtained for the 2 ns lifetime, since the competing effects of the low- and high-lifetime scenarios counterbalance each other.

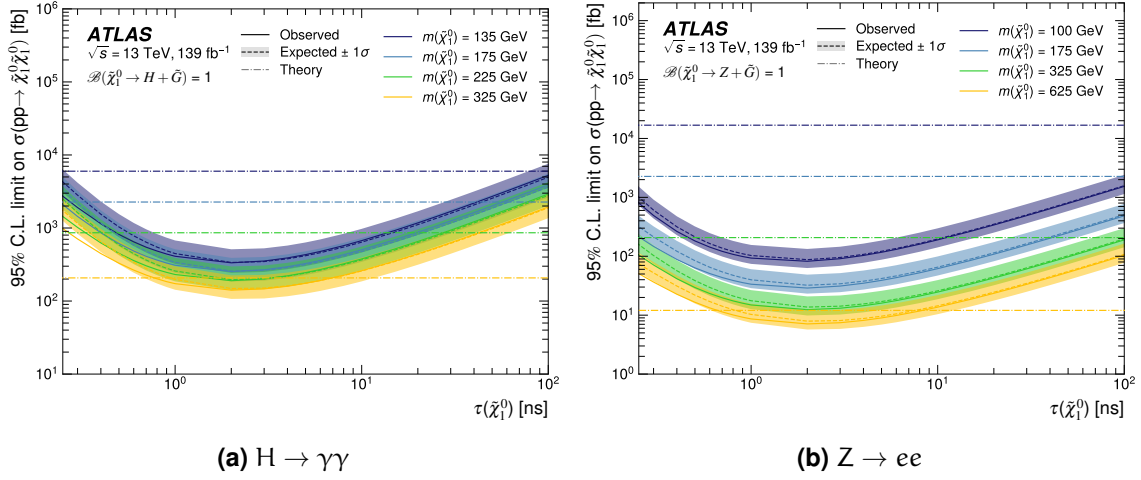


Figure 13.5: 95 % C.L. limit on $\sigma(\text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ lifetime for the different decay modes $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G}) = 1$ and $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1$. The different colored bands represent the upper limits for different $\tilde{\chi}_1^0$ masses. Included are the theoretical expectations for each mass hypothesis, calculated from a GMSB SUSY model that assumes nearly degenerate $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^0$.

Figure 13.6 shows the upper limit on the $\sigma(\text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ as a function of the decay mode of the $\tilde{\chi}_1^0$ to $H + \tilde{G}$ and $Z + \tilde{G}$. The upper limits are computed for different $\tilde{\chi}_1^0$ masses and the 2 ns $\tilde{\chi}_1^0$ lifetime. Stronger exclusions are obtained for higher masses and larger values of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G})$. The stronger exclusion for larger values of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G})$ is because of $\mathcal{B}(Z \rightarrow ee)$ is larger than $\mathcal{B}(H \rightarrow \gamma\gamma)$. Thus, the signal yield for the $Z \rightarrow ee$ decay mode is higher, resulting in a stronger exclusion.

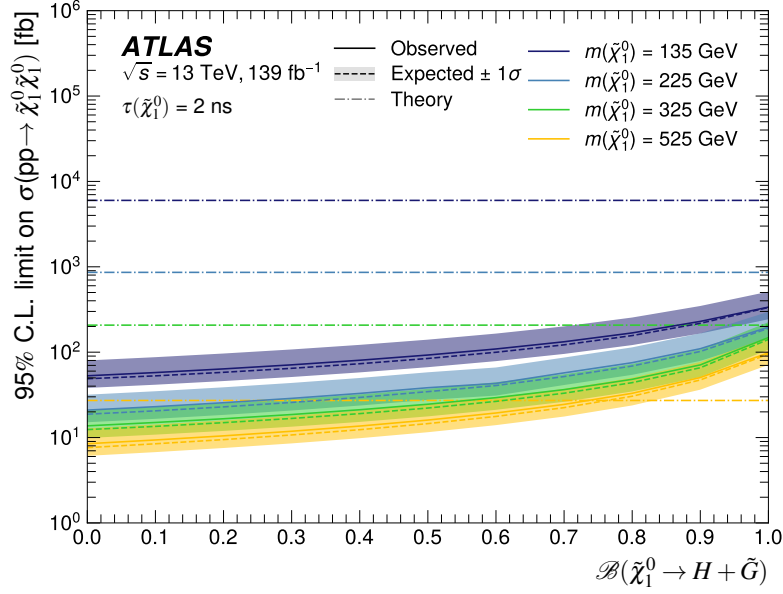


Figure 13.6: 95% C.L. limits on $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ in fb as a function of $\tilde{\chi}_1^0$ branching ratio to the SM Higgs boson, where $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1 - \mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G})$. Several signal hypotheses are overlaid that are labeled by the $\tilde{\chi}_1^0$ mass, all with a fixed $\tilde{\chi}_1^0$ lifetime of 2 ns. Included are the theoretical expectations for each mass hypothesis, calculated from a GMSB SUSY model that assumes nearly degenerate $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^0$.

When setting the upper limit on the $\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$, the $\tilde{\chi}_1^0$ masses and lifetimes which are below the theoretical cross section are excluded at a 95% C.L. Figure 13.7 summarizes the excluded $\tilde{\chi}_1^0$ masses and lifetimes for various values of the $\tilde{\chi}_1^0$ branching ratio to the Higgs boson. The masses and lifetimes to the left of the curves are excluded at a 95% C.L. This elegant interpretation highlights the sensitivity of this search. Signal models with $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G}) = 1$ are excluded up to $m(\tilde{\chi}_1^0) = 370$ GeV, and models with $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1$ are excluded up to $m(\tilde{\chi}_1^0) = 700$ GeV, and for $\tilde{\chi}_1^0$ lifetimes in the range 0.25–1000 ns.

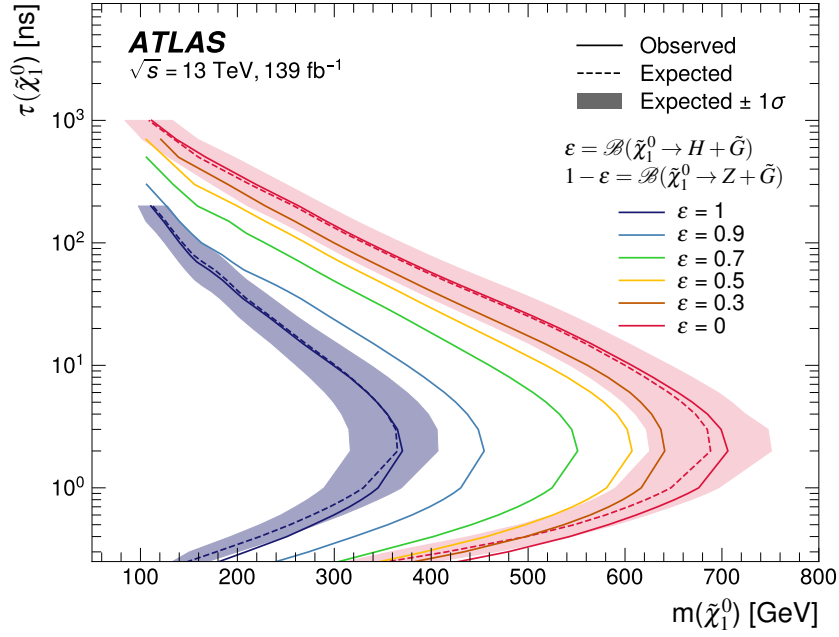


Figure 13.7: 95% C.L. exclusion limits on the target signal hypothesis, for $\tilde{\chi}_1^0$ lifetime in ns as a function of $\tilde{\chi}_1^0$ mass in GeV. The overlaid curves correspond to different decay hypotheses, where the $\tilde{\chi}_1^0$ decays to $H + \tilde{G}$ or $Z + \tilde{G}$ such that $\mathcal{B}(H + \tilde{G}) + \mathcal{B}(Z + \tilde{G}) = 1$. The curve shown in red represents the decay hypothesis where the $\tilde{\chi}_1^0$ decays to $Z + \tilde{G}$ with a 100% branching ratio. The curve shown in blue represents the decay hypothesis where the $\tilde{\chi}_1^0$ decays to $H + \tilde{G}$ with a 100% branching ratio.

Figure 13.8 shows the excluded values of the $\tilde{\chi}_1^0$ mass as a function of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G})$ and the $\tilde{\chi}_1^0$ lifetime. Signal models with the parameters enclosed by the contours of constant $\tilde{\chi}_1^0$ mass are considered to be excluded at a 95% C.L. This interpretation illustrates how the exclusion limits evolve in the three-dimensional signal grid.

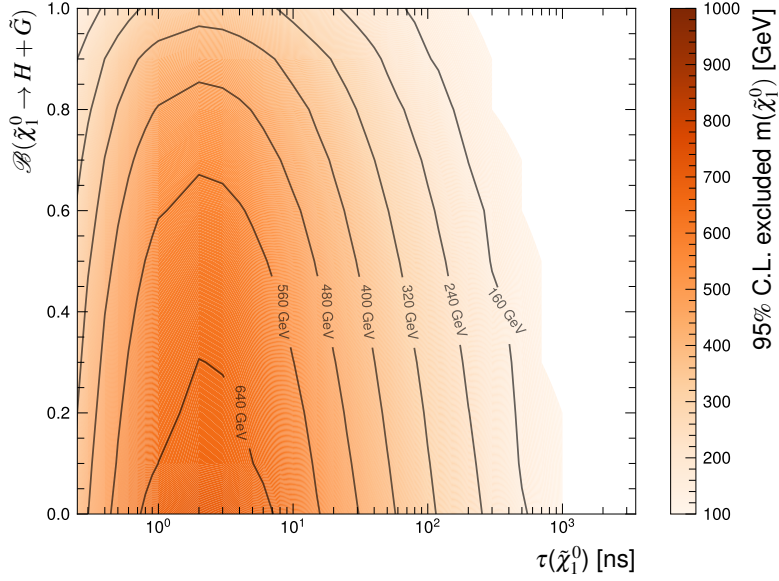


Figure 13.8: Excluded values of the $\tilde{\chi}_1^0$ mass as a function of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G})$ and the $\tilde{\chi}_1^0$ lifetime. Signal models with the parameters enclosed by the contours of constant $\tilde{\chi}_1^0$ mass are considered to be excluded at a 95% C.L..

13.3 Model-Independent Result

The model-independent result is determined by a *cut-and-count* analysis of the expected and observed number of events in the timing bin $t_{\text{avg}} \in [0.9, 12)$ ns. The selection of the photon candidates is listed in Table 13.1. For the model-independent search, no vertexing categorization is required. Therefore, the cut-and-count represents a semi-generic search for a pair of delayed photons.

The model-independent results are summarized in Table 13.2. The discovery region predicts 10.8 ± 2.2 (cf. Table 12.2) and The observed number of events is 4. This prediction is consistent with the observation of a narrower timing distribution in the SR than in the background template.

Parameter	Selection Value
Photon multiplicity	≥ 2
Trigger	
2015–2016	HLT_g35_loose_g25_loose
2017–2018	HLT_g35_medium_g25_medium
Timing [ns]	$\in (-12, 12)$
$\Delta\eta_{\gamma\gamma}$	> 0.1
$m_{\gamma\gamma}$ [GeV]	> 60
V_R [mm]	$\in (0, 1500)$
$ V_Z $ [mm]	< 3740

Table 13.1: Selection of the photon candidates for the model-independent results.

Selection	Data	Total Background	p_0	Z (σ)	N^{excl} Events
SR, $t_{\text{avg}} > 0.9$ ns	4	10.8 ± 2.2	0.97	-1.96	15.0

Table 13.2: Results for the model-independent analysis. The expected number of events and the uncertainty on the expected number of events are calculated using a fit to the ρ -inclusive t_{avg} distribution, with $t_{\text{avg}} \in [0.0, 0.9)$ ns and extrapolated to the $t_{\text{avg}} \in [0.9, 12)$ ns bin. The compatibility of the observed events with the background-only expectation is given by the p_0 -value, its corresponding significance Z , and the 95% CL upper limit on the number of excluded events under the background-only hypothesis.

Chapter 14

Conclusion

There be dragons.

Devanshu Panchal

Ph.D. Thesis

This thesis presents a search for displaced production of Higgs bosons or Z^0 bosons, originating from the decay of a neutral long-lived particle (LLP) and reconstructed in the decay modes $H \rightarrow \gamma\gamma$ and $Z \rightarrow ee$. The search utilizes the full Run 2 data set recorded by the ATLAS detector at the LHC, corresponding to an integrated luminosity of 139 fb^{-1} of pp collisions at the center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. The search exploits the capabilities of the LAr calorimeter to precisely measure the arrival times and trajectories of electromagnetic objects. The geometric design of the LAr calorimeter is used to develop the novel Trackless Calo-Vertexing method which provides a localized vertex position for the production of the displaced Higgs/Z boson. The timing measurements, with an offline timing calibration to obtain a sub-nanosecond resolution, enhances the search for delayed photons/electrons produced from the displaced Higgs/Z boson. The Trackless Calo-Vertexing and the photon timing provide a handle on the critical features of the signal.

The background estimation is a data-driven approach since the non-Gaussian tails of the LAr calorimeter timing distributions are not properly modeled in Monte Carlo simulation. The background model is derived from events in the control region, defined as a low- E_T^{miss} , high- $m_{\gamma\gamma}$ region. The sensitive analysis variables are the average of the two photon times, t_{avg} , and the two-dimensional displacement for the localized secondary vertex, ρ , calculated using the calo-vertexing method. The statistical analysis framework consists of performing a simultaneous fit to the average photon timing distribution in categories of secondary vertex displacement. The fit is performed using the background model from the control region, the simulated signal, and the observed data.

No significant excess over the background expectation is observed. In the unblinded signal region, one event in the highest timing and vertexing bin is

observed with features compatible with a satellite collision. Results of the search are presented as 95% C.L. upper limits on the di- $\tilde{\chi}_1^0$ production cross section, scanning the $\tilde{\chi}_1^0$ mass, lifetime, and the branching ratio of the $\tilde{\chi}_1^0$ to the SM Higgs/Z boson. The signal model assumes a nearly degenerate electroweakino triplet ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm$) with $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G}) + \mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1$. For the signal models with $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H + \tilde{G}) = 1$, the highest excluded $\tilde{\chi}_1^0$ mass is nearly 370 GeV, and excluded lifetimes at lower $\tilde{\chi}_1^0$ mass ranges from 0.25 to 100 ns. For signal models with $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow Z + \tilde{G}) = 1$, the highest excluded $\tilde{\chi}_1^0$ mass is nearly 700 GeV, and the excluded lifetimes at lower $\tilde{\chi}_1^0$ mass span a large range from 0.25 ns to 1 μ s.

This thesis presents a foray into the search for displaced diphoton vertices. The search establishes the first dedicated sensitivity to displaced and delayed diphoton vertices; however, this search is by no means complete. The analysis intentionally kept two regions blinded for future analyses. These regions include: a low- E_T^{miss} , low- $m_{\gamma\gamma}$ region for a possible model with the production of a displaced Higgs/Z boson without E_T^{miss} ; and a high- E_T^{miss} , high- $m_{\gamma\gamma}$ region for a possible model with the production of new, displaced, di-electromagnetic resonance with high E_T^{miss} .

LLPs constitute some of the most promising, yet weakly constrained classes of signatures explored at the LHC. Recent years have seen an increased interest in exploring SUSY, or other exotic models, with LLP signatures. Extended applications of the LAr calorimeter measurements and methodologies may broaden the sensitivity to a large phase space of long-lived BSM signatures. The timing measurements from the LAr calorimeter were already used in previous searches [76, 78] and are being explored for a future delayed electron analysis. One of the key contributions of this thesis is the development of the trackless calo-vertexing method to localize the position of the secondary vertex that represents the production of the displaced Higgs/Z boson. This calo-vertexing method could be used to complement displaced track measurements, such as the large radius tracking (LRT) algorithm [160].

Since July 2022, LHC started its third data-taking period (Run 3) with pp collisions at an increased center-of-mass energy of $\sqrt{s} = 13.6$ TeV. Besides an increase in the center-of-mass energy, LHC will also deliver pp collisions at a higher instantaneous luminosity and a higher number of average collisions per bunch crossing. The changes in the beam configuration will result in an overall increase in the

detector occupancy, while the first-level trigger (L1) bandwidth will remain at 100 kHz during Run 3. In preparation for Run 3, the LAr calorimeter upgraded its on-detector hardware and readout electronics to add another readout chain that will collect data in parallel to the existing readout chain. The new readout chain called the "*Digital Trigger*" [161], is the first of the two-stage upgrade to the calorimeter readout electronics. The Digital Trigger aims to retain the rate of the L1 trigger without increasing the E_T^{miss} thresholds. Besides maintaining the E_T^{miss} thresholds for existing triggers, the Digital Trigger readout chain is also being used to develop new LLP triggers which explicitly target displaced or delayed objects. At the end of Run 3, the LHC will deliver $\sim 300 \text{ fb}^{-1}$ of pp collision data. Besides a rough doubling of statistics compared to the Run 2 data set, the use of novel LLP triggers as well as the use of new reconstruction techniques such as Calo-Vertexing or LRT will allow for future analyses to explore a broad phase space for LLPs.

The next several years will be an exciting period for the search for LLPs. ATLAS has developed dedicated algorithms to identify, reconstruct, and record events with an LLP candidate. State-of-the-art techniques in machine learning are being employed to reinterpret existing results with a special focus on models with LLPs, and new experiments — MATHUSLA [162] and ANUBIS [163] — dedicated to LLP searches have been proposed. The growing interest in LLPs provides a new avenue to search for the "missing" particles. The work presented in this thesis in the field of LLPs is just the start of the trail, one which might hold the discovery of the long-sought particles which could help complete our understanding of the subatomic world.

Appendices

Appendix A

Satellite Collisions

This appendix discusses the observation of satellite collisions across the analysis regions. Figure A.1 shows the prevalence of satellite events in data. The photon object selections are applied to the events, and to classify an event as a satellite collision an additional requirement of at least one photon with $|t_\gamma| \in [4, 6]$ ns is applied. Table A.1 provides the predicted and measured number of satellite events across the analysis regions. The predictions are divided into the pospos and the negneg categories since the satellite collisions are asymmetric as observed in Figure 8.9. The table lists the predicted events which pass the photon object selection, preselection, and also for the various analysis regions. The predictions in the validation and signal regions are calculated by scaling the number of satellite events predicted in the CR with the fraction of events to the target region yield.

Timing Category	Photon Object Selection	Preselection	CR	VR- E_T^{miss}	VR-time	SR
pospos	1,581,992	729,189	113,100	55,535	-	18,260
# Satellites Pred.	-	-	-	1.5 ± 1.0	-	0.5 ± 0.3
# Satellites Meas.	44	21	3	0	-	1
negneg	1,505,129	703,917	108,121	53,548	17,827	-
# Satellites Pred.	-	-	-	0.5 ± 0.5	0.17 ± 0.17	-
# Satellites Meas.	36	12	1	2	0	-

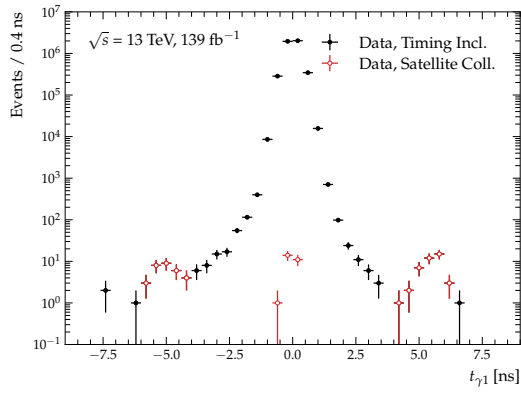
Table A.1: Predicted and measured number of satellite collision events across the analysis regions.

The prevalence of the satellite collision events as a function of the event-level, photon-kinematic, and analysis-sensitive variables is shown in Figures A.2–A.3. As evident from the figures, the satellite collision events have a similar distribution to the events produced in the primary bunch crossings.

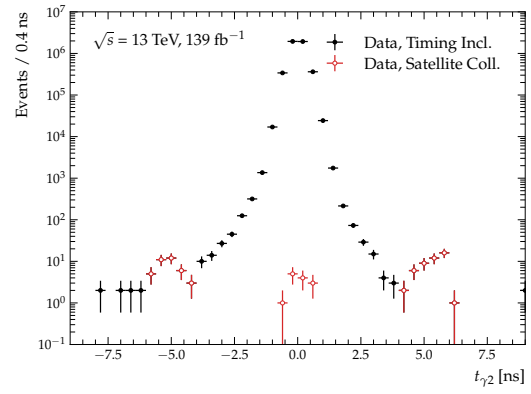
Figure A.4 shows the ρ - z and x - y projections of the signal region event in the highest timing and vertexing bin. The event is identified with the Run 359593, and event number 761048468. The characteristics of the photon-candidate events were discussed in Section 13.1; however, a detailed description of the event- and the object-level information is provided in Table A.2

Sensitive Analysis Variables		
t_{avg}	3.13 ns	
Vertexing ρ	559.7 mm	
Event-level Variables		
$E_{\text{T}}^{\text{miss}}$	79.5 GeV	
$\langle \mu \rangle$	43.9	
PV_z	−29.8 mm	
V_{R}	554.2 mm	
V_z	78.7 mm	
Photon-object Variables		
	Leading Photon	Subleading Photon
Photon ID	Medium	Medium
p_{T}	65.3 GeV	32.4 GeV
$E(\gamma)$	187.1 GeV	32.7 GeV
$E_{\text{cell}}^{\text{maxE gain}}$	Medium	High
$E_{\text{cell}}^{\text{maxE}}$	53.4 GeV	6.3 GeV
$\eta(\gamma)$	−1.71	0.12
t_{γ}	5.82 ns	0.45 ns
z_{γ}	2578.1 mm	−11.6 mm
Diphoton Variables		
$m_{\gamma\gamma}$	108.6 GeV	
$p_{\text{T}}^{\gamma\gamma}$	84.4 GeV	
$\Delta\eta(\gamma_1, \gamma_2)$	1.8	
$\Delta\phi(\gamma_1, \gamma_2)$	1.13	

Table A.2: Event- and object-level characteristics of the signal region event in the highest timing and vertexing bin.

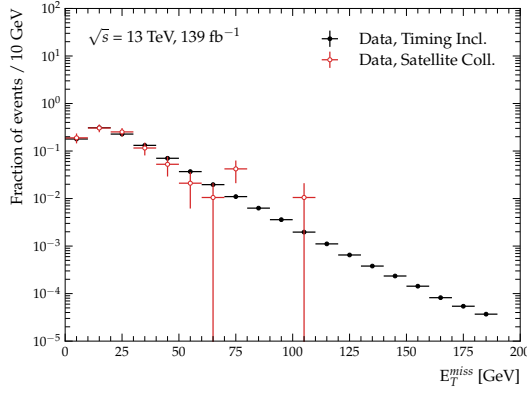


(a) $t_{\gamma 1}$

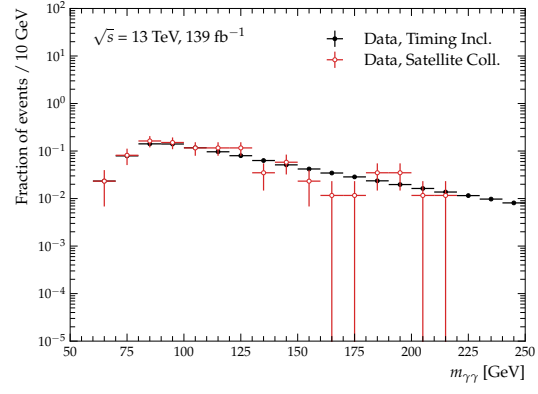


(b) $t_{\gamma 2}$

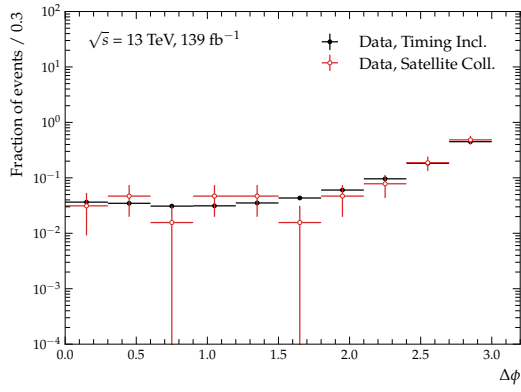
Figure A.1: Satellite collision events observed in the photon timing distributions in data. The photon object selections are applied to the recorded events; for the satellite events, an additional requirement of at least one photon with $|t_{\gamma}| \in [4, 6] \text{ ns}$ is applied.



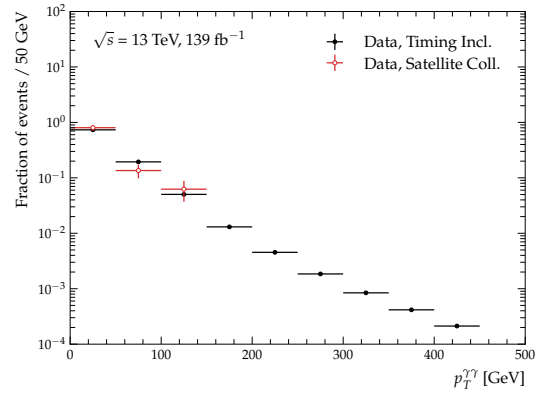
(a) E_T^{miss}



(b) $m_{\gamma\gamma}$

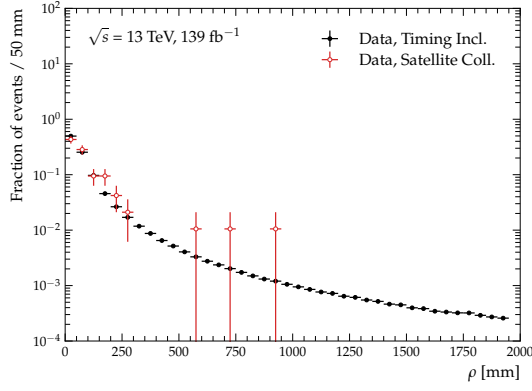


(c) $\Delta\phi(\gamma_1, \gamma_2)$

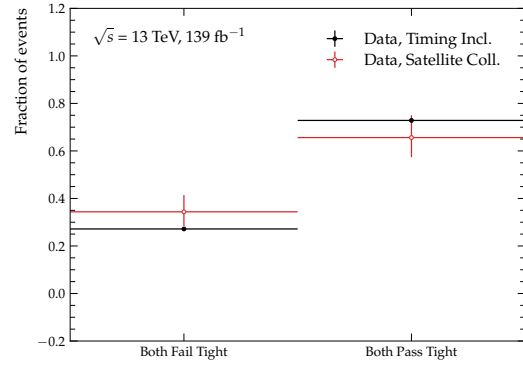


(d) $p_T^{\gamma\gamma}$

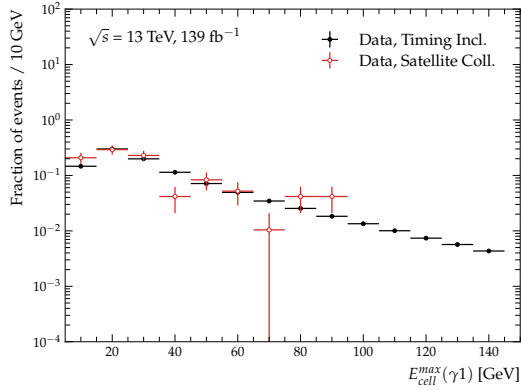
Figure A.2: Prevalence of the satellite collisions for the E_T^{miss} , $m_{\gamma\gamma}$, $\Delta\phi(\gamma_1, \gamma_2)$, $p_T^{\gamma\gamma}$ distributions. The events in data are required to pass the photon object selections.



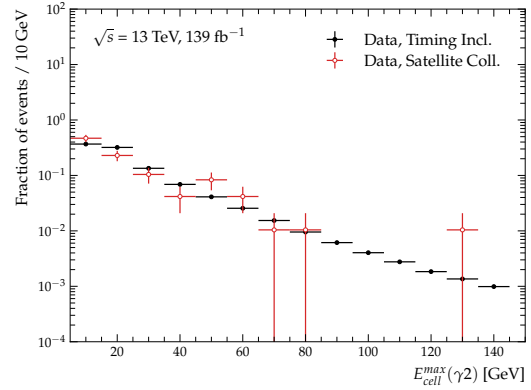
(a) ρ



(b) Photon ID working point



(c) $E_{\text{cell}}^{\text{max}} E(\gamma_1)$



(d) $E_{\text{cell}}^{\text{max}} E(\gamma_2)$

Figure A.3: Prevalence of the satellite collisions for the ρ , photon ID, $E_{\text{cell}}^{\text{max}} E(\gamma_1)$, $E_{\text{cell}}^{\text{max}} E(\gamma_2)$ distributions. The events in data are required to pass the photon object selections.

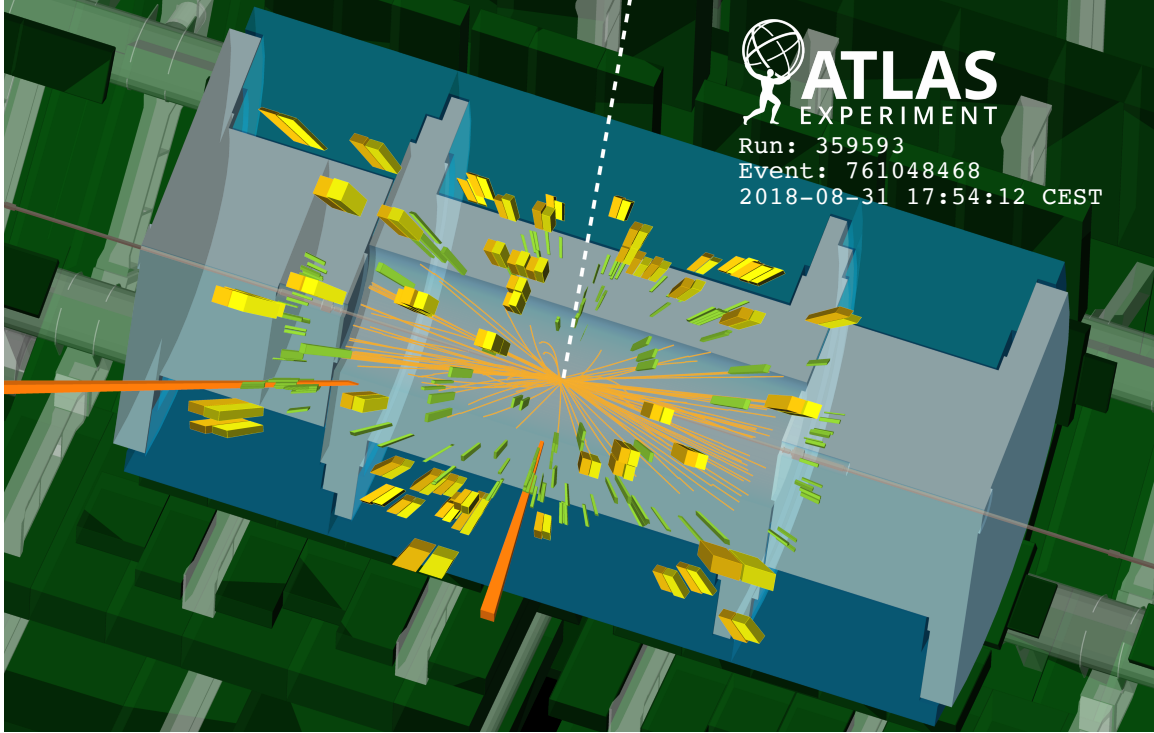


Figure A.4: Three-dimensional visualization of a candidate diphoton event (Run 359593, Event 761048468) as recorded by the ATLAS detector. A cutout of the LAr electromagnetic calorimeter is shown in light blue, the Tile calorimeter is shown in dark blue, the muon chambers are shown in dark green, and the barrel toroid is shown in white. The orange lines are the tracks formed from the signals recorded by the tracking detectors. These tracks originate from the pp hard scatter vertices and are used to determine the primary vertex. The green and yellow blocks are energy deposits in the LAr electromagnetic and Tile calorimeters, respectively. The two orange towers are the reconstructed candidate photons. The dashed white line shows the missing transverse energy, E_T^{miss} , carried by invisible particles produced in the event. The "endcap" photon which is reconstructed in the electromagnetic endcap calorimeter, has a time of arrival at the calorimeter of 5.82 ns with respect to the primary vertex. The "barrel" photon which is reconstructed in the electromagnetic barrel calorimeter, has a time of arrival at the calorimeter of 0.5 ns with respect to the primary vertex. The endcap photon time-of-arrival at the calorimeter is consistent with a particle produced in the collision of the satellite proton bunches. Similarly, the barrel photon time-of-arrival at the calorimeter is consistent with a particle produced in the collision of the nominal proton bunches. Therefore, this delayed diphoton event is most likely a satellite collision overlaid with the nominal proton collision.

Appendix B

Timing Investigations

B.1 Timing Distributions Across Timing Quadrants

The selected events are required to have the same sign of the photon candidates, as shown in Section 9.2. Figure B.1 shows the t_{avg} distributions in the four timing quadrants. The events in this figure are required to pass the analysis preselections (cf. Table 9.1) and the CR selections (cf. Table 9.3). As evident from the figure, the same-sign timing quadrants — pospos and negneg — have a similar timing distribution. The opposite-sign timing quadrants — posneg and negpos — have similar distributions but are different compared to either the pospos or the negneg distribution. The difference between the same-sign and the opposite-sign timing quadrants manifests because the opposite-sign timing values are more likely to have t_{avg} closer to zero compared to t_{avg} calculated with same-sign timing values.

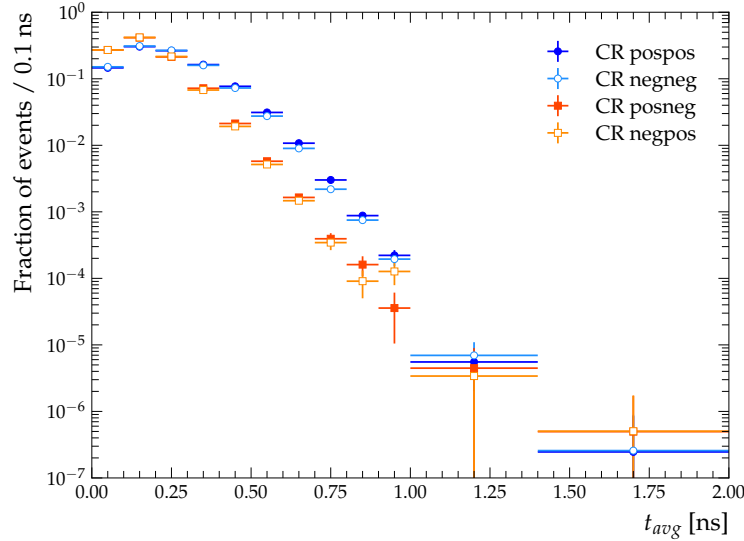


Figure B.1: Comparison of t_{avg} distribution across the timing quadrants. The events are required to pass the photon preselections and also the CR selections with the exclusion of the photon-sign requirement. The t_{avg} is calculated by taking the absolute value before performing the average.

B.2 Timing Variable Candidates

In selecting the optimal timing analysis variable from the two photon times, four candidate variables were considered. The three candidates are:

1. Individual photon times ($t_{\gamma 1}, t_{\gamma 2}$)
2. Average of the two photon times (t_{avg})
3. Difference of the two photon times (t_{diff})

Figure B.2 shows the timing distributions of the CR data and the simulated signal events. For the data events, the CR selections are applied, and the $E_{\text{cell}}^{\text{max}}$ distributions are reweighted to match the expected distribution in the SR. Additionally, a Gaussian fit is performed, and the fit parameters are added to the plots. Of the three candidates, the t_{avg} variable provides an excellent signal-to-background separation. Thus, compared to the individual photon times, or the difference of the photon times, t_{avg} is chosen as one of the sensitive variables for the analysis.

Although the average of the two photon times, t_{avg} , was chosen as one of the sensitive analysis variables, a study was performed to use a weighted mean of the two photon times; the timing resolution of the two photons are used as the weights. However, the weighted timing does not perform significantly better than the average of the two photon times, so t_{avg} was chosen as the sensitive variable.

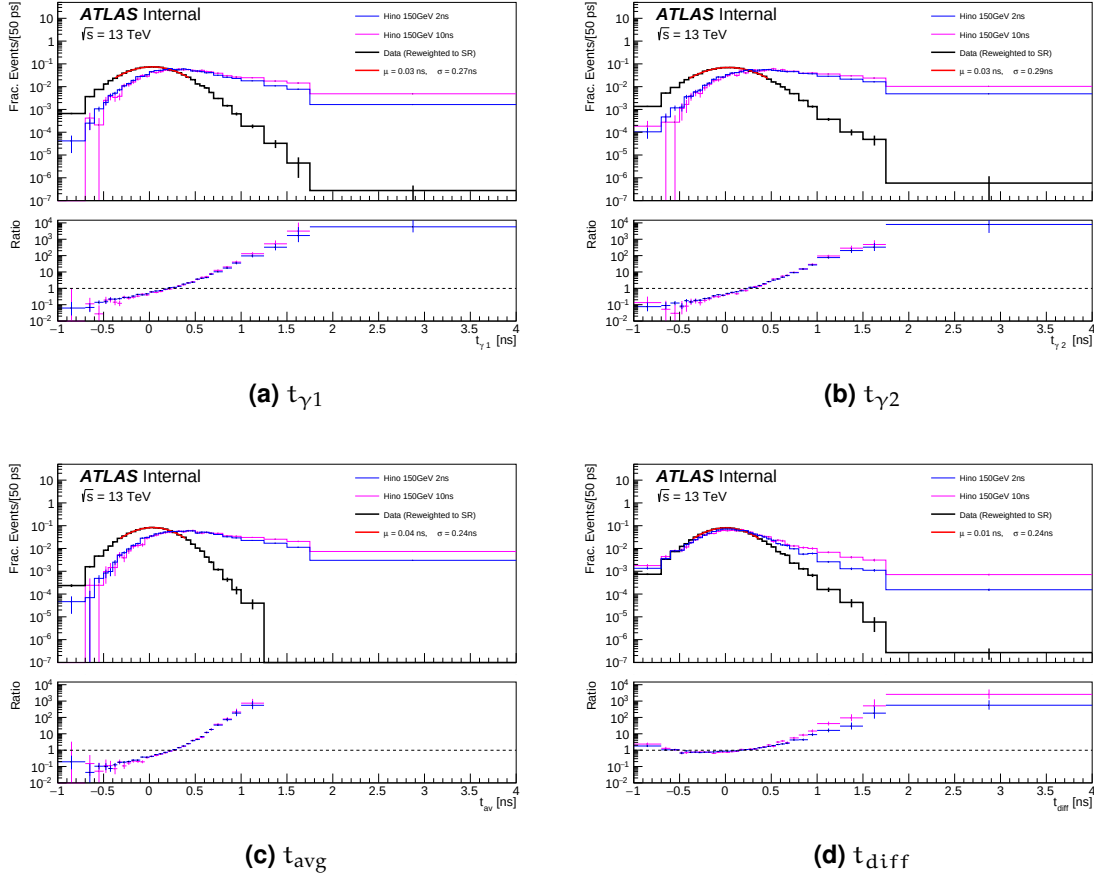


Figure B.2: Comparison of the various choices of the timing variable constructed from the two photon timing values. The four distributions show the CR data events whose $E_{\text{cell}}^{\text{maxE}}$ spectra are reweighted to spectra of the SR events. The data events are compared to signal distributions which are the $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$, $\tau(\tilde{\chi}_1^0) = 2 \text{ \& } 10 \text{ ns}$ simulated samples.

B.3 Lifetime Reweighting

The lifetime reweighting procedure is used to interpret signal lifetimes below, between, and above the lifetimes of the generated signal grid points. The reweighting procedure and the range of the lifetime values are described in this section. The primary limitation to the lifetime reweight range is the limited statistics, especially for events that contain a $\tilde{\chi}_1^0$ with a very high decay time. The reweighting procedure uses the truth information from the simulated signal to determine the proper decay time of the $\tilde{\chi}_1^0$ for each event. To calculate the reweights, the $\tilde{\chi}_1^0$ which decays into

the forces $Z \rightarrow ee$ or $H \rightarrow \gamma\gamma$ is considered. In the rare case where an event contains two displaced di-EM resonances, one $\tilde{\chi}_1^0$ is chosen at random, with the requirement that the $\tilde{\chi}_1^0$ decays before the Inner Detector (ID). Since the fraction of events where both the $\tilde{\chi}_1^0$ decay into di-EM final-state objects is small, the vertex misidentification in events where the incorrect $\tilde{\chi}_1^0$ decay is selected is negligible.

Figure B.3 shows the lifetime reweighting procedure validated using HyyHSM and ZeeZSM signal samples. In this figure, the HyyHSM and ZeeZSM signal samples generated at $\tau(\tilde{\chi}_1^0) = 2, 10, 50$ ns are reweighted to target $\tilde{\chi}_1^0$ lifetimes of 2, 10, and 20 ns. The reweighted source distributions are compared to the target distribution. As evident from the figure, the reweighted source distributions are in agreement with the target distribution.

The lifetime reweighting is performed to achieve target lifetimes in the range of 0.25 ns to 1000 ns. Lifetime reweight for target lifetimes below (above) 0.25 ns (1000 ns) are at the boundary of the exclusion limit. Therefore, the lifetime reweighting is performed in the range [0.25, 1000] ns.

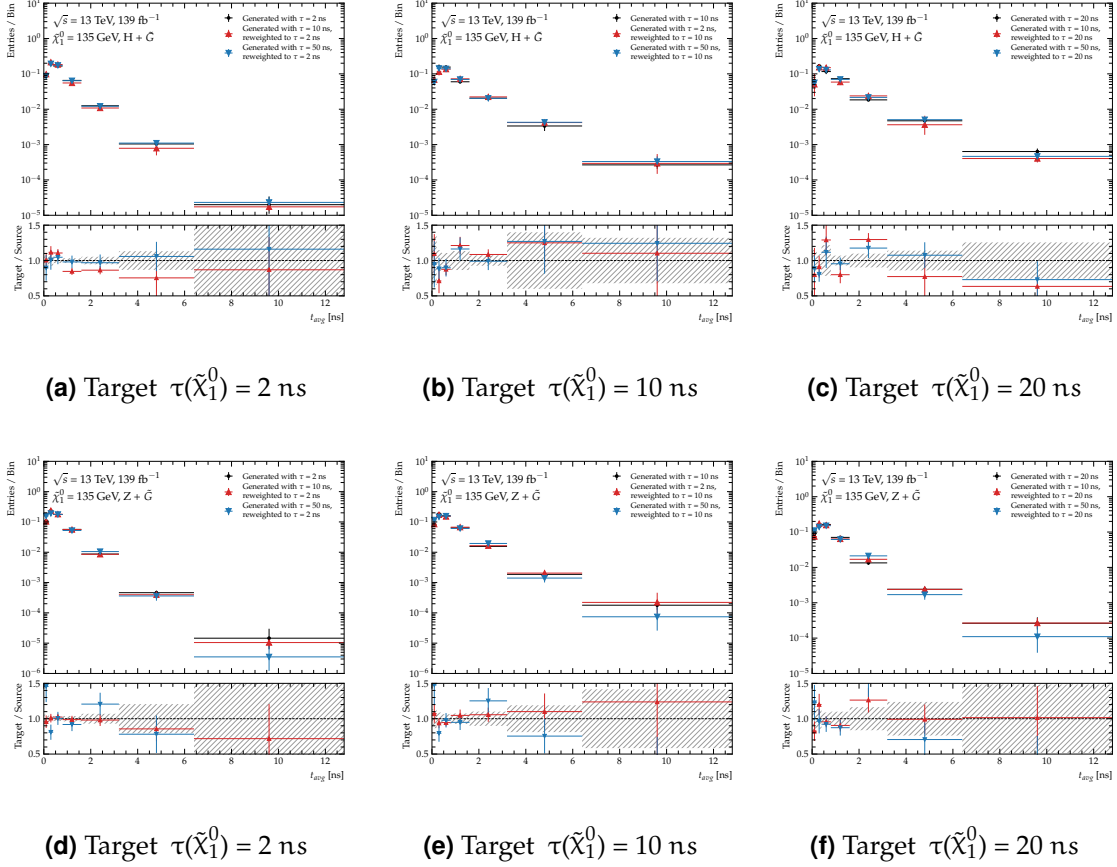
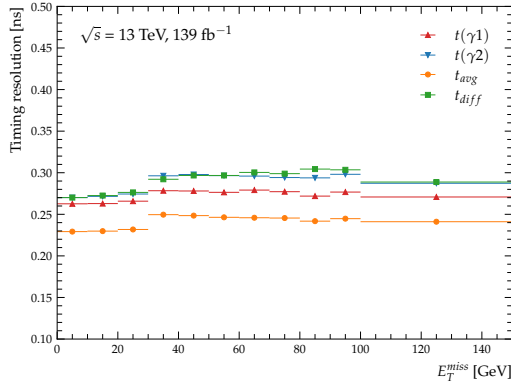


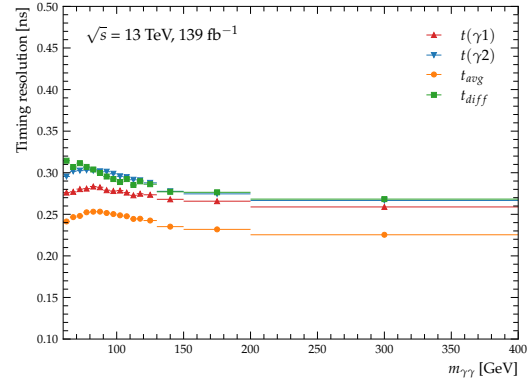
Figure B.3: Validation of the lifetime reweighting procedure. Each plot shows the t_{avg} distribution for two types of lifetime reweighting and for the t_{avg} distribution from the simulated signal sample generated at the target $\tilde{\chi}_1^0$ lifetime. In each plot, the t_{avg} distribution from the simulated sample generated at the target $\tilde{\chi}_1^0$ lifetime is shown with black-filled circles. The simulated sample generated at a higher $\tilde{\chi}_1^0$ lifetime and reweighted down to the target lifetime is shown with red filled up-arrows. The simulated sample generated at a lower $\tilde{\chi}_1^0$ lifetime and reweighted up to the target lifetime is shown with blue-filled down-arrows. In each plot, the bottom panel shows the ratio of the reweighted distributions to the target distribution. The black hatched band represents the statistical uncertainty of the target t_{avg} distribution. Figures B.3a–B.3c show examples of the lifetime reweighting procedure for the HyyHSM samples with $m(\tilde{\chi}_1^0) = 135$ GeV and $\tau(\tilde{\chi}_1^0) = 2, 10, 20$ ns. Similarly, Figures B.3d–B.3f show examples of the lifetime reweighting procedure for the ZeeZSM samples with $m(\tilde{\chi}_1^0) = 135$ GeV and $\tau(\tilde{\chi}_1^0) = 2, 10, 20$ ns.

B.4 Timing Resolutions

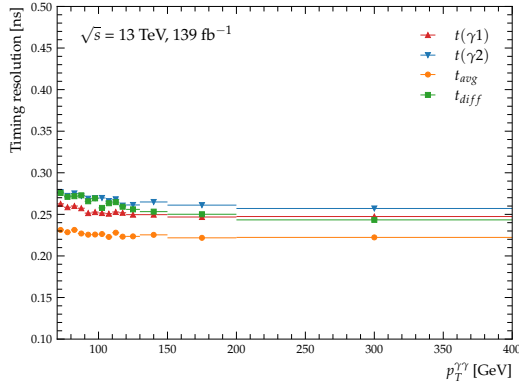
As described in Section 13.1 the origin of the differences between the background model and the SR t_{avg} distribution is not clear. The timing resolutions for various combinations of the two photon times for several critical analysis variables are shown in Figure B.4. The analysis preselection requirements listed in Table 9.3 are applied and no form of $E_{\text{cell}}^{\text{maxE}}$ reweighting, photon purity rescaling, or residual timing shift (cf. Sections 10.1–10.3) is performed. The timing resolutions shown in Figure B.4 are distinguishable, but have a relatively flat distribution in each of the critical analysis regions. This relative flatness indicates the analysis did not fail to capture any striking correlations between the two photon times. Additionally, the similarity of t_{avg} and t_{diff} distributions also indicates that the correlation between the two photon times is not the culprit either.



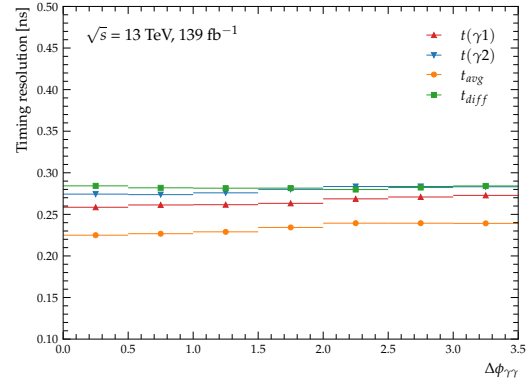
(a) E_T^{miss}



(b) $m_{\gamma\gamma}$



(c) $p_T^{\gamma\gamma}$



(d) $\Delta\phi(\gamma_1, \gamma_2)$

Figure B.4: Resolutions of the various timing distribution for the critical analysis variables. The four distributions show the resolution of the timing distribution as a function of E_T^{miss} , $m_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, and $\Delta\phi(\gamma_1, \gamma_2)$.

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Vita

Devanshu Kiran Panchal was born in Mumbai, India. He did his elementary and high school education in Mumbai and moved to the University of Illinois at Urbana–Champaign (UIUC) for his undergraduate studies. From UIUC, he earned a Bachelor’s degree in Physics and a minor in Mathematics. He went to the University of Texas at Austin (UT Austin) for his doctoral studies. At UT Austin, he worked on the Liquid Argon (LAr) Calorimeter at the ATLAS experiment. During his time at UT Austin, he worked on the development and testing of a custom-designed, radiation-tolerant analog-to-digital converter(ADC), dubbed the COLUTA ADC. The COLUTA ADC is one of the key components for the Phase-II upgrade of the readout electronics. He then went to CERN, in 2020, to work on the Phase-I upgrade of the readout electronics. Despite the COVID-19 pandemic, he managed to work as a detector coordinator to ensure the timely installation of the Phase-I upgrade electronics. During his time at CERN, he also worked on developing software for the online, data-taking software for the LAr calorimeter.

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