

Doctoral Dissertation

**Search for higgsinos with compressed
mass spectra in final states with
low-momentum leptons using 140 fb^{-1} of
proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$**

Kaito Sugizaki

Department of Physics, Graduate School of Science,
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

July 2024



Abstract

Although the Standard Model (SM) has attained substantial success in describing particle physics phenomena, it has confronted major challenges such as its inability to explain dark matter and to address the hierarchy problem. Hence, the ultimate goal of modern particle physics is to discover the physics beyond the SM. Supersymmetry (SUSY), a yet-to-be-found symmetry between fermions and bosons, is one of the leading candidates of physics beyond the SM. Under the framework of Minimal Supersymmetric Standard Model (MSSM) with R -parity conservation, scenarios with light higgsinos are viable candidates of new physics, as they are consistent with constraints from collider experiments and dark matter observations. Experiments at the Large Hadron Collider (LHC) have the potential to search for such scenarios, however, the sensitivities are limited by experimental difficulties owing to the compressed mass spectra of the higgsinos.

The dissertation presents the search for higgsinos using 140 fb^{-1} of proton-proton collisions at center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ at the LHC, targeting final states with low-momentum leptons. The sensitivity to higgsinos in the target mass regions has been considerably improved by the development and application of low- p_T lepton track identification algorithms and the introduction of neural-network-based event selection techniques. No significant excess in data has been observed in the unblinded dataset, and exclusion limits have been set on the target higgsino scenarios. In the context of the simplified higgsino model with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, higgsino mass of up to 130 GeV has been excluded for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1\text{--}2 \text{ GeV}$. This mass splitting region has been covered for the first time at the LHC, extending the limit by about 40 GeV in higgsino mass, where the original limit was set by the LEP2 experiment.

Contents

1	Introduction	1
1.1	The Standard Model	2
1.1.1	Overview	2
1.1.2	Remaining problems of the Standard Model	4
1.2	Supersymmetry	6
1.2.1	MSSM and R-parity	7
1.2.2	Solutions to the remaining problems of the Standard Model	9
1.2.3	The mass spectrum of the MSSM	11
1.2.4	Experimental constraints	17
1.3	Target scenario and search strategy	26
1.3.1	Target scenario	26
1.3.2	Previous searches	27
1.3.3	Analysis strategy	30
2	Experimental Setup	33
2.1	Large Hadron Collider	33
2.2	ATLAS detector	35
2.2.1	Coordinate system	35
2.2.2	Magnet system	36
2.2.3	Inner Detector	37
2.2.4	Calorimeters	39
2.2.5	Muon spectrometers	42
2.2.6	Luminosity detectors	46
2.2.7	Trigger and Data Acquisition system	47
3	Data and Simulated Event Samples	49
3.1	Dataset	49
3.2	Trigger	49
3.3	Monte-Carlo sample simulation	51
3.3.1	Signal MC sample generation	51
3.3.2	Background MC sample generation	52
3.3.3	Detector and pileup simulation	53
4	Standard Object Reconstruction and Identification	54
4.1	Track	54
4.2	Vertex	56

4.3	Topo-cluster	56
4.4	Jet	57
4.5	Electron	60
4.6	Muon	61
4.7	Overlap removal	63
4.8	Missing transverse momentum	63
5	Development of Low-p_T Lepton Track Identification	65
5.1	Low- p_T electron track	65
5.1.1	Identification algorithm	66
5.1.2	Optimization of selection criteria	75
5.1.3	Performance measurement with data and efficiency calibration	78
5.2	Low- p_T muon track	81
6	Event Selection	86
6.1	Analysis strategy	86
6.2	Preselection and variables used to define the Signal Regions	88
6.2.1	Event kinematic variables	88
6.2.2	Variables used for low- p_T lepton track preselection	89
6.3	Parameterized neural network for event selection	91
6.3.1	Input variables	92
6.3.2	Model and training	92
6.3.3	Performance	96
6.3.4	Application	98
6.4	Signal Region definition	98
7	Methodology of Background Estimation	100
7.1	Background components	100
7.2	Data-driven estimation of 1L + fake lepton track background	101
7.3	MC estimation of 1L + true lepton track background	104
7.4	Validation strategy	104
7.5	Summary of CR and VR definitions	106
7.6	Estimation results in the Signal Region	108
8	Systematic Uncertainties	109
8.1	Experimental uncertainties	109
8.2	Theoretical uncertainties	111
8.3	Analysis specific uncertainties	112
8.4	Impact on background estimation	113
9	Statistical Analysis	115
9.1	Likelihood function	115
9.2	Hypothesis testing	116
9.3	Fit configuration	117

10 Results	119
10.1 Background-only fit	119
10.2 Model-dependent fit	129
10.3 Model-independent fit	135
11 Discussion	137
11.1 Slight excess observed for the muon channel	137
11.2 Comparison to previous approaches and other experiments	137
11.3 Interpretation in $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ vs $m(\tilde{\chi}_1^0)$	139
11.4 Impact on SUSY mass parameters	142
11.5 Prospects in future experiments	143
12 Conclusion	146
13 Contributions to the Level-1 Muon Trigger System in Run 3	147
13.1 Run 3 upgrade of the Level-1 muon trigger	147
13.2 Realization of integrated control	147
13.3 Development of a new software-based readout system	149
13.4 Commissioning and stable operation	149
13.5 Summary	151
A Signal MC Samples	153
B Details of Low-p_T Lepton Track Identification	157
B.1 Input variables of LPET ID DNN	157
B.2 Performance measurement and calibration	164
B.2.1 MC samples	164
B.2.2 Event and track selection criteria	164
B.2.3 $dR(\text{trk}, \gamma)$ distributions for each track p_T bin	164
B.2.4 Efficiency and scale factors for fake electron tracks	164
C Signal yields	171
D Signal contamination	174
D.1 Control Regions	174
D.2 Validation Regions	174

Preface

The dissertation covers my works on search for higgsinos in the ATLAS experiment [1] during my PhD program at The University of Tokyo in 2019–2024. The leading channel of pure higgsino searches in ATLAS have been carried out by requiring a high- p_T hadronic jet and targeting signatures with high missing momentum (E_T^{miss}) from higgsinos and two low- p_T leptons (e^+e^- , $\mu^+\mu^-$) originating from the higgsino decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$. Given that higgsino mass splitting $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ is typically of a few GeV, the sensitivity had been largely limited due to difficulties in signal event tagging. This research overcomes these difficulties by developing and exploiting new low- p_T lepton identification algorithms with dedicated optimizations for leptons in low- p_T regimes, extending the search sensitivity to higgsinos with compressed mass spectra. The research uses the full “LHC Run 2” dataset taken in 2015–2018, corresponding to an integrated luminosity of 140 fb^{-1} .

In 2019–2020, as a preparatory work to search for new physics in the ATLAS experiment, I have conducted phenomenological studies by parameter scans and proposed that a supersymmetric model having higgsinos with compressed mass spectra is one of the most motivated candidates of new physics under the current experimental and theoretical constraints. Targeting higgsino searches in final states with low- p_T leptons, I started R&D studies on the identification algorithm of low- p_T electrons in 2021. As the studies gradually converged in 2022, I shifted my focus onto the search analysis for higgsinos with compressed mass spectra. The following are brief descriptions of my significant contributions to these works.

Development of the low- p_T electron identification algorithm

The new low- p_T electron identification algorithm has been designed to identify low- p_T electrons primarily based on the track information given by the ATLAS inner detectors, with less emphasis on energy clusters in the calorimeters, which are not reconstructed for p_T below 2 GeV. Using deep neural network (DNN), the algorithm exploits the track and calorimeter cluster information in an inclusive manner. I have conducted all of its development works by myself: studies and selection of input detector variables, design of the DNN structure, determination of the selection criteria and performance evaluation, and efficiency measurement with data. Namely, I have created the low- p_T electron identification algorithm from scratch and succeeded in its implementation to the undermentioned search analysis for higgsinos.

Search for higgsinos with compressed mass spectra

Fully benefiting from the newly developed low- p_T lepton identification algorithms, a dedicated analysis method has been developed to maximize the search sensitivity to higgsinos with compressed mass spectra. The new method targets higgsino pair

production processes with $\tilde{\chi}_2^0$ involved: $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$. Similar to past searches, a high- p_T hadronic jet and high E_T^{miss} are required. However, instead of two leptons identified with a standard algorithm, one standardly identified lepton and one low- p_T lepton identified by the newly developed, dedicatedly optimized algorithm are required to further increase sensitivity to models with small $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. The analysis has been developed for two channels, where the target leptons could be either two electrons or two muons.

As the main analyzer of an international analysis team, I have successfully designed and established the whole analysis chain of both electron and muon channels. For event selection, I have adopted a newly developed parametrized neural network (pNN) method. Since the event and track kinematics largely depend on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, the selection must be optimized for each target $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ to exploit the event topology characteristics. I have designed the pNN to use $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ as one of the input variables of the network, thus enabling efficient selections of signal-like events for every target $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. By combining the pNN-based event selection and the low- p_T lepton identification, significant background suppression has been achieved. Not only have I developed these analysis procedures for the electron channel, but I have also significantly modified, optimized, and finalized the procedures for the muon channel, using the low- p_T muon identification algorithm and analysis software frameworks developed by Dr. Hiroaki Hibi (member of ATLAS and Kobe University until March 2022).

I have developed an optimal method for signal extraction by requiring high low- p_T lepton identification score and high pNN score. The dominant Standard Model background process is W +jets, where the lepton from $W \rightarrow \ell\nu$ is identified, and a prompt hadronic track fakes the low- p_T lepton track. To eliminate MC modeling uncertainties and to realize an accurate prediction, I have designed and conducted a new background estimation method common to both channels, which estimates the dominant fake lepton background in a data-driven way. I have also evaluated the effects of systematic uncertainties and the final sensitivity to target higgsino models by developing a statistical framework for both electron and muon channels.

In addition, I have contributed to ATLAS in terms of detector upgrade and operation. During my master's program at The University of Tokyo in 2019–2021, I have made significant contribution to the development, commissioning, and operation of the ATLAS Level-1 endcap muon trigger system for the ongoing LHC Run 3, which started in 2022. I have achieved two main projects: the realization of integrated control of the new Run 3 system and the development and integration of a new software-based readout system for the Level-1 endcap muon trigger. During my PhD program, I have continued making crucial contributions as a leading expert by means of commissioning and stable operation.

This dissertation has a primary focus on the search analysis for higgsinos with compressed mass spectra. Section 1 gives an overview of the theoretical backgrounds of this search and introduces the target scenario and search strategy of the analysis. Section 2 reviews the experimental apparatus: LHC and ATLAS detector. Section 3 describes the data and Monte-Carlo samples used in the analysis. Section 4 summarizes the standard objects used in the analysis. Section 5 discusses the development of low- p_T lepton track identification methods. Sections 6–9 describe the principal methods of the analysis: event

selection, background estimation, and statistical analysis including evaluation of systematic uncertainties. Section 10 shows the final results of the analysis. Section 11 gives some discussion of the results and future prospects of the analysis. Section 12 concludes the search analysis for higgsinos. As additional material, Section 13 gives a brief summary of the contributions to the Run 3 TGC and Level-1 muon trigger systems. The appendices are dedicated to details of the search analysis for higgsinos and low- p_T lepton identification algorithms used in the analysis.

1. Introduction

What are the fundamental constituents of matter and force? The ultimate question has been pursued throughout the history of human beings. As of today, we deem *elementary particles* to be the most fundamental constituents. The nature of these elementary particles is described to a great extent by the Standard Model (SM) of particle physics [2–11]. The SM has succeeded in explaining experimental results with high precision.

Nevertheless, the SM has some major deficiencies, both experimentally and theoretically. One leading example is its failure to explain the existence of dark matter (DM), strongly implied by multiple observation results of the universe [12–15]. Anisotropies of the cosmic microwave background (CMB) and gravitational lensing effects indicate that the mass content of dark matter in the whole universe should be 5-6 times more than that of ordinary baryonic matter. Another issue of the SM is its incapability of giving masses to the neutrinos. Although the SM expects neutrinos to be massless, observations of neutrino oscillations [16, 17] indicate massive neutrinos. On the theoretical side, the SM incorporates strong, weak, and electromagnetic interactions, however, it does not unify them as a single force. The theoretical framework for the unification of these three forces is called “Grand Unified Theory (GUT)” [18–20], primarily motivated by the observation of charge quantization. In addition, the inclusion of gravitational interactions and solutions to the hierarchy problem [21] would be further necessary for a more fundamental theory.

The utmost priority of modern particle physics is to therefore search for new physics beyond the SM and to provide a clearer picture of microscopic phenomena surrounding us. Although there are many theories which do so, none of them have been experimentally confirmed to be correct. *Supersymmetry* (SUSY) [22–28] is one of the leading candidates of physics beyond the SM, which has the potential of such impact. SUSY imposes transformation relations between bosons and fermions, predicting new particles with quantum numbers identical to their SM partners with the exception of spin; SM fermions (bosons) have bosonic (fermionic) SUSY partners. Theoretical aspects of SUSY was first proposed and established in the 1970s in the context of quantum field theory and string theory [29, 30]. Although experimental evidence of SUSY has not been found, the theory has been held in high regard due to its strong prediction power and theoretical robustness [31]. SUSY not only gives viable candidates of DM [32, 33], but also gives solutions to grand unification and the hierarchy problem [34–39]. In light of arguments regarding naturalness [38, 40], higgsinos, SUSY partners of the Higgs bosons¹, are expected to have mass near the electroweak scale [41–44].

¹In the minimal supersymmetric extension of the SM, an additional Higgs doublet is introduced, causing the model to have four additional Higgs bosons.

This dissertation presents searches for higgsino production at the Large Hadron Collider (LHC), targeting scenarios where the lightest supersymmetric particles (LSPs) are assumed to be higgsinos, within the framework of the minimal supersymmetric extension of the SM (MSSM) [45, 46] with R-parity conservation. In such scenarios, the higgsinos are expected to have compressed mass spectra, with typical mass splitting values of $\mathcal{O}(0.1\text{--}1\text{ GeV})$. The general strategy of this search is to target signatures with two low-momentum leptons, which are emitted when the second-lightest neutral higgsino decays into the lightest neutral higgsino.

1.1 The Standard Model

1.1.1 Overview

The Standard Model (SM) of particle physics is a quantum field theory which best describes three of the four known forces which interact between elementary particles or fields: strong, weak, and electromagnetic interactions, with the exception of gravity. The SM incorporates the three interactions as internal symmetries, formulated as the unitary gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

The particle content of the SM is as follows. Table 1.1 shows the fermions in the SM. The fermions are roughly divided into two categories: quarks which interact with strong force and leptons which do not. Quarks and leptons both consist of three generations, hence we introduce a notation using generation numbers $i = 1, 2, 3$. Up, charm, and top quarks are denoted as up-type quarks $u^i = u, c, t$, and down, strange, and bottom quarks are denoted as down-type quarks $d^i = d, s, b$. Similarly for leptons, the three neutrinos are denoted as $\nu^i = \nu_e, \nu_\mu, \nu_\tau$, whereas charged leptons are denoted as $e^i = e, \mu, \tau$. In addition, the $SU(2)_L$ gauge group engages only with left-handed fermions, hence, the left-handed components of the fermions constitute $SU(2)_L$ doublets, whereas the right-handed components constitute $SU(2)_L$ singlets. In summary, the SM fermions are denoted as

$$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}, u_R^i, d_R^i, e_R^i. \quad (1.1)$$

Although quarks constitute $SU(3)_C$ triplets and have color charges, the color notations will be omitted below.

Table 1.2 shows the bosons in the SM. There are four gauge bosons: gluons which mediate strong force, W and Z bosons which mediate weak force, and photons which mediate electromagnetic force. The Higgs boson emerges as a result of the Higgs mechanism [9–11], where the spontaneous breaking of electroweak $SU(2)_L \times U(1)_Y$ gauge symmetry gives mass to W and Z bosons.

The interactions of particles in the SM are characterized by the Lagrangian³ of the SM. The Lagrangian formalism is a convenient way to describe quantum field theories with Lorentz invariance and gauge invariances. The SM Lagrangian could be written as

$$\mathcal{L}_{SM} = \mathcal{L}_F + \mathcal{L}_G + \mathcal{L}_H + \mathcal{L}_Y, \quad (1.2)$$

²The upper mass limit on ν_e shown here is the upper mass limit on $\bar{\nu}_e$.

³Lagrangian density to be precise.

Table 1.1: The SM fermions and their characteristics [47]. Although neutrinos are assumed to be massless in the SM, upper limits on the mass are shown, since they are known to be massive². The errors of electron and muon masses have been omitted as they are negligibly small.

	Generation	Name	Notation	Mass	T^3	Y_W	Spin
Quarks	First	Up	u	$2.16^{+0.49}_{-0.26}$ MeV	+2/3	1/2	
		Down	d	$4.67^{+0.48}_{-0.17}$ MeV	-1/3	1/2	
	Second	Charm	c	1.27 ± 0.02 GeV	+2/3	1/2	
		Strange	s	$93.4^{+8.6}_{-3.4}$ MeV	-1/3	1/2	
	Third	Top	t	172.69 ± 0.30 GeV	+2/3	1/2	
		Bottom	b	$4.18^{+0.03}_{-0.02}$ GeV	-1/3	1/2	
Leptons	First	Electron neutrino	ν_e	< 0.8 eV	0	1/2	
		Electron	e	0.511 MeV	-1	1/2	
	Second	Mu neutrino	ν_μ	< 0.19 eV	0	1/2	
		Muon	μ	105.658 MeV	-1	1/2	
	Third	Tau neutrino	ν_τ	< 18.2 eV	0	1/2	
		Tau	τ	1776.86 ± 0.12 MeV	-1	1/2	

Table 1.2: The SM bosons and their characteristics [47].

	Name	Notation	Mass	Charge	Spin
Vector bosons	Gluon	g	0	0	1
	W boson	$W^\pm$	80.377 ± 0.012 GeV	± 1	1
	Z boson	Z	91.1876 ± 0.0021 GeV	0	1
	Photon	γ	0	0	1
Scalar boson	Higgs	H	125.25 ± 0.17 GeV	0	0

where

$$\mathcal{L}_F = \overline{Q}_L^i i\gamma^\mu D_\mu Q_L^i + \overline{u}_R^i i\gamma^\mu D_\mu u_R^i + \overline{d}_R^i i\gamma^\mu D_\mu d_R^i + \overline{L}_L^i i\gamma^\mu D_\mu L_L^i + \overline{e}_R^i i\gamma^\mu D_\mu e_R^i \quad (1.3)$$

$$\mathcal{L}_G = -\frac{1}{4}G_{\mu\nu}^\alpha G^{\alpha\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (1.4)$$

$$\mathcal{L}_H = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \quad (1.5)$$

$$\begin{aligned} \mathcal{L}_Y = & -y_L^{ij} \left\{ \overline{L}_L^{0i} \Phi e_R^{0j} + \overline{e}_R^{0i} \Phi^\dagger L_L^{0j} \right\} - y_d^{ij} \left\{ \overline{Q}_L^{0i} \Phi d_R^{0j} + \overline{d}_R^{0i} \Phi^\dagger Q_L^{0j} \right\} \\ & - y_u^{ij} \left\{ \overline{Q}_L^{0i} \tilde{\Phi} u_R^{0j} + \overline{u}_R^{0i} \tilde{\Phi}^\dagger Q_L^{0j} \right\}. \end{aligned} \quad (1.6)$$

$\mathcal{L}_F$ is the kinetic term of the fermions, where γ^μ ($\mu = 0, 1, 2, 3$) are the Dirac matrices, and D_μ are the covariant derivatives for each of the fermionic fields listed in Eq. (1.3). $\mathcal{L}_G$ is the kinetic term of gauge bosons, where $G_{\mu\nu}^\alpha$ ($\alpha = 1, \dots, 8$), $W_{\mu\nu}^a$ ($a = 1, 2, 3$), and $B_{\mu\nu}$ are the field strength tensors of the $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ gauges, respectively. $\mathcal{L}_H$ is the Higgs terms, with Φ representing the Higgs doublet; the first term is the kinetic term, and the second term is the Higgs potential crucial for the Higgs mechanism. $\mathcal{L}_Y$ is the Yukawa interaction terms representing the couplings between the Higgs boson and the SM fermions, where the y^{ij} are the Yukawa coupling constants.

1.1.2 Remaining problems of the Standard Model

Although it has been proven that the SM describes the microscopic phenomena surrounding us with high precision, it is strongly believed that it is merely a low-energy approximation; the SM cannot be *the ultimate theory of everything* as it contains major experimental and theoretical problems. This section briefly highlights some of those problems.

Dark matter

Cosmological observations have shown that ordinary baryonic matter does not fully account for the mass content of the universe; it is expected that there be 5-6 times more mass content from “invisible” matter, which we refer to as *dark matter (DM)*. Early evidences of DM come from rotation curves of galaxies [48, 49]; the rotation velocities of galaxies cannot be explained without the assumption of unordinary matter that we do not observe. Fig. 1.1 displays an example of a rotation curve. The velocity of the galaxy exhibits a flat behavior at large distances from the galactic center; this implies the existence of galactic halo, namely DM, in these regions. Further evidences from gravitational lensing effects [50] and anisotropies of CMB [12, 13] also strongly suggest the existence of DM.

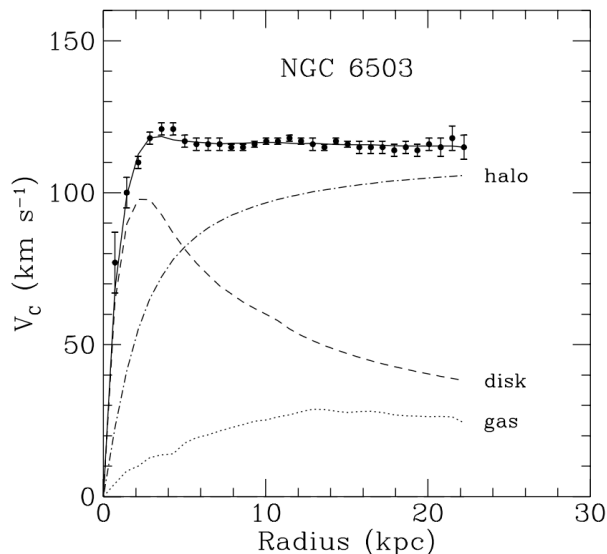


Figure 1.1: Rotation curve of galaxy NGC 6503 [51]. The points show the rotation velocities of the galaxy with respect to the distances from its center. The solid line shows the fitted velocity with the assumption of DM. The dotted, dashed, and dash-dotted lines each represents contributions from gas, disk, and DM (halo).

There are many proposed candidates of DM. Elementary particles beyond the SM, such as Weakly Interacting Massive Particles (WIMPs) and axions, are leading DM candidates. WIMP DM candidates are expected to be thermal relics. As the temperature of the universe dropped below the WIMP mass scale, the number density of WIMPs would decrease exponentially, eventually to a point where their interactions with surrounding particles become negligible. This “freeze out” of WIMPs would lead to a substantial

number of WIMP relics in the universe today. In the case in which the freeze out is explained by a s-channel annihilation, the relic density of a WIMP is roughly given by

$$\Omega_{\text{WIMP}} h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right)^{-1}, \quad (1.7)$$

where $\langle \sigma v \rangle$ is the self annihilation cross section [52]. Since the DM relic density is expected to be $\Omega_{\text{DM}} h^2 \simeq 0.12$ from recent observations [13], if all DM is assumed to be WIMPs, typical WIMP mass would be $\mathcal{O}(100\text{--}1000)$ GeV.

Nonthermally produced objects such as axions [53–56] and dynamical, non-particle-like objects such as primordial black holes [57–59] are also considered as DM candidates.

Grand Unified Theory and unification of gravity

The SM is a gauge theory based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry. The relation

$$Q = T^3 + \frac{Y_W}{2} \quad (1.8)$$

holds between electric charge Q , the third component of weak iso-spin number T^3 , and weak hypercharge Y_W . The electric charges of charged leptons $Q(l)$ and down quarks $Q(d)$ is related by $|Q(l)| = 3|Q(d)|$. As the weak hypercharges are arbitrary, there is no reason for this integer multiple relation to hold. Moreover, the sum of weak hypercharges for all fermion content must be zero for $U(1)_Y$ gauge anomaly to cancel, which is indeed the case for the SM. This quantized nature of charges has led to the idea of Grand Unified Theory (GUT), which unifies the strong and electroweak interactions into a single force described by a larger symmetry group. Therefore, the SM is strongly believed to be merely a low-energy approximation of GUT.

Another motivation of GUT is the agreement of gauge couplings at high energy. Following the renormalization group equations, the gauge couplings of $SU(3)_C$, $SU(2)_L$, and $U(1)_Y$ run to certain values at higher energy scales. The three couplings are expected to take similar values at a certain grand unification scale Λ_{GUT} , which also indicates the existence of GUT.

Although it is beyond the scope of modern particle physics experiments, it is worthwhile to mention that the *fundamental theory of everything* is expected to also accommodate gravity. However, theories of quantum gravity cannot be constructed straightforwardly, as gravitational interaction is non-renormalizable. Theories such as loop quantum gravity [60–64] and string theory have been studied as leading candidates of gravity unification theories.

Hierarchy problem and the fine-tuning of the Higgs mass

The SM cannot explain the large disparity between the energy scale of the weak force and the gravitational force. This problem is often referred to as the *hierarchy problem*. A famous manifestation of the hierarchy problem is the *fine-tuning problem* of the Higgs mass. As already shown in Table 1.2, it has been discovered that the mass of the Higgs boson is 125 GeV, however, this value is unnaturally small compared to the energy scale of ultraviolet theories. If the SM is a low-energy approximation of a more general theory

having an energy scale of Λ , calculations of the Higgs mass squared will include quadratic radiative corrections with a magnitude of $\mathcal{O}(\Lambda^2)$:

$$m_h^2 = m_{h0}^2 + \Delta m_h^2, \quad \Delta m_h^2 \sim \Lambda^2, \quad (1.9)$$

where m_{h0} is the bare mass of the Higgs. If we assume the SM to hold up to the Planck scale $M_{\text{Pl}} \sim 10^{19}$ GeV, this implies the cancellation of 34 orders of magnitude between m_h^2 and Δm_h^2 . For this to happen in the SM, “fine-tuning” of the parameters is necessary, which would be quite unnatural. To solve this problem of fine-tuning, it is therefore required to extend the SM in a way that the quadratic radiative corrections to the Higgs mass disappear in principle.

1.2 Supersymmetry

Supersymmetry (SUSY) is a symmetry between bosons and fermions. It introduces a supersymmetric operator Q , which transforms bosonic states to fermionic states and vice versa:

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q|\text{Fermion}\rangle = |\text{Boson}\rangle. \quad (1.10)$$

In particular, Q and its hermitian conjugate $Q^\dagger$ are fermionic operators, or spinors, which satisfy the following anti-commutation and commutation relations⁴:

$$\{Q_\alpha, Q_\alpha^\dagger\} = -2\sigma_{\alpha\dot{\alpha}}^\mu P_\mu \quad (1.11)$$

$$\{Q_\alpha, Q_\beta\} = 0, \quad \{Q_\alpha^\dagger, Q_\beta^\dagger\} = 0, \quad (1.12)$$

$$[Q_\alpha, P^\mu] = 0, \quad [Q_\alpha^\dagger, P^\mu] = 0. \quad (1.13)$$

α and β are spinor indices, and P^μ is the ordinary four-momentum generator of spacetime translations.

In SUSY, single-particle states belong to the irreducible representations of the supersymmetric algebra called supermultiplets. Each supermultiplet contains both fermion and boson states, related to each other by Eq. (1.10). These fermion and boson states are referred to as SUSY partner particles of each other. Since the squared-mass operator $-P_\mu P^\mu$ commutes with Q and $Q^\dagger$, the fermion and boson belonging to the same supermultiplet have equal mass. In addition, the supersymmetric operators also commute with operators of gauge transformations; the particles in the same supermultiplet have the same quantum numbers, including color, weak isospin, and electric charge.

It can be further proved that the number of degrees of freedom for fermions and bosons in the same supermultiplet are equal [28]. Accordingly, two main types of supermultiplets partake in supersymmetric extensions of the SM: chiral supermultiplets and vector supermultiplets. A chiral supermultiplet consists of a two-component Weyl fermion and a complex scalar field. A vector supermultiplet consists of a vector boson and a two-component Weyl fermion. Considering renormalizability and gauge transformation properties, it is expected that the Weyl fermions in chiral supermultiplets correspond to the SM fermions, and the vector bosons in vector supermultiplets correspond to the SM

⁴We assume here that there is only one set of supersymmetric operators. In the case of *extended supersymmetry*, there could be multiple sets: Q_α^A , where $A = 1, \dots, \mathcal{N}$.

gauge bosons. Consequently, the SM fermions should have scalar partner particles, and the SM gauge bosons should have Weyl fermion partner particles. Additionally, the SM Higgs boson is expected to reside in a chiral supermultiplet, as scalar fields can only be in chiral supermultiplets.

In the low-energy world surrounding us, we have not observed any SUSY partner particles which have the same mass as the SM particles. Therefore, it is natural to assume that SUSY is a broken symmetry, as is the case with electroweak symmetry in the SM. As a result of supersymmetry breaking, SUSY partner particles are expected to have masses beyond the reach of current SUSY search experiments.

1.2.1 MSSM and R-parity

The Minimal Supersymmetric Standard Model (MSSM) [45, 46] is the minimal supersymmetric extension of the SM and has been the major target of many studies searching for hints of SUSY. Table 1.3 shows the particle content of the MSSM. As already mentioned, each SM fermion has a SUSY partner scalar, and each SM gauge boson has a SUSY partner fermion.

Table 1.3: Particle content of the MSSM. Here, the $SU(2)_L$ gauge bosons have been denoted as W bosons and the $U(1)_Y$ gauge boson as B boson. In general, the notation of SUSY particles are represented as the notation of the corresponding SM particle with a tilde.

SM			SUSY		
Name	Notation	Spin	Name	Notation	Spin
Quark	$\begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, u_R^i, d_R^i$	1/2	Squark	$\begin{pmatrix} \tilde{u}_L^i \\ \tilde{d}_L^i \end{pmatrix}, \tilde{u}_R^i, \tilde{d}_R^i$	0
Lepton	$\begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}, e_R^i$	1/2	Slepton	$\begin{pmatrix} \tilde{\nu}_L^i \\ \tilde{e}_L^i \end{pmatrix}, \tilde{e}_R^i$	0
Gluon	g	1	Gluino	$\tilde{g}$	1/2
W boson	$W^\pm, W^0$	1	Wino	$\tilde{W}^\pm, \tilde{W}^0$	1/2
B boson	B	1	Bino	$\tilde{B}$	1/2
Higgs boson	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	0	Higgsino	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1/2

For the Higgs sector, the MSSM requires an additional Higgs doublet. This is because a consistent quantum field theory requires the cancellation of gauge anomalies, part of which demands the sum of weak hypercharges for all fermions to be zero. As the fermion partner of Higgs bosons, the higgsinos, give a non-zero contribution, another Higgs supermultiplet is required to cancel this contribution. Hence, two Higgs supermultiplets, H_u and H_d , are introduced, each having hypercharge of $Y_W = 1$ and $Y_W = -1$. Moreover, two Higgs supermultiplets are necessary to give correct Yukawa couplings for the SM fermions, without introducing large flavor-changing neutral currents; H_u gives masses to up-type quarks, whereas H_d gives masses to down-type quarks and charged leptons.

The MSSM Lagrangian and soft-supersymmetry breaking

One phenomenological motivation of SUSY is to provide a solution to the hierarchy problem by cancelling the quadratic divergent radiative corrections to the Higgs mass. To maintain this solution even in the presence of supersymmetry breaking, the idea of “soft” supersymmetry breaking is introduced. Therefore, the effective Lagrangian of the MSSM can be written as

$$\mathcal{L}^{\text{MSSM}} = \mathcal{L}_{\text{SUSY}}^{\text{MSSM}} + \mathcal{L}_{\text{soft}}^{\text{MSSM}}, \quad (1.14)$$

where $\mathcal{L}_{\text{SUSY}}^{\text{MSSM}}$ includes all gauge and Yukawa interactions which are invariant under supersymmetry, and $\mathcal{L}_{\text{soft}}^{\text{MSSM}}$ violates supersymmetry but only includes mass terms and coupling parameters having positive mass dimensions. Particularly, $\mathcal{L}_{\text{soft}}^{\text{MSSM}}$ is given by

$$\begin{aligned} \mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \widetilde{W} \widetilde{W} + M_1 \widetilde{B} \widetilde{B} + \text{c.c.} \right) \\ & - \left(\tilde{u} \mathbf{A}_u \tilde{Q} H_u - \tilde{d} \mathbf{A}_d \tilde{Q} H_d - \tilde{e} \mathbf{A}_e \tilde{L} H_d + \text{c.c.} \right) \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}). \end{aligned} \quad (1.15)$$

The first line represents mass terms for the gluino, wino, and bino, with M_3, M_2 , and M_1 being the mass parameters. The second line gives the trilinear interaction terms for squarks and sleptons, and the third line gives the mass terms for those SUSY scalar particles. The parameters $\mathbf{A}_u, \mathbf{A}_d, \mathbf{A}_e$ are trilinear coupling matrices, and $\mathbf{m}_Q^2, \mathbf{m}_L^2, \mathbf{m}_u^2, \mathbf{m}_d^2, \mathbf{m}_e^2$ are mass matrices, each having 3×3 dimension in generation space. The last line gives supersymmetry-breaking contributions to the Higgs potential, where $m_{H_u}^2, m_{H_d}^2$, and b are squared-mass terms. If the hierarchy problem were to be solved, all of the soft-SUSY breaking parameters should have a value near a general mass scale m_{soft} , not much larger than the TeV scale:

$$M_1, M_2, M_3, \mathbf{A}_u, \mathbf{A}_d, \mathbf{A}_e \sim m_{\text{soft}} \quad (1.16)$$

$$\mathbf{m}_Q^2, \mathbf{m}_L^2, \mathbf{m}_u^2, \mathbf{m}_d^2, \mathbf{m}_e^2, m_{H_u}^2, m_{H_d}^2, b \sim m_{\text{soft}}^2. \quad (1.17)$$

In the MSSM, SUSY breaking is introduced explicitly as soft SUSY-breaking terms. It is worthwhile to mention that this is only an effective way of describing the phenomenological consequences of spontaneous SUSY breaking. Besides, it is presumed that supersymmetry is spontaneously broken in a “hidden sector” and its effects are “mediated” to the MSSM sector in a non-trivial way. This is because if the origin of SUSY breaking were in the MSSM sector, this would indicate the existence of a SUSY scalar particle lighter than its partner SM fermion, which is ruled out by experiment.

There are several viable candidates for models which induce spontaneous supersymmetry breaking. One is gravity-mediated supersymmetry breaking scenario, which include the effects of supergravity (SUGRA) [65–72]. Supergravity further extends supersymmetry from a global symmetry to a local symmetry, thus incorporating gravitational effects. In this case, the gravitino, a SUSY partner fermion of the graviton with spin of $3/2$, is introduced. Other candidates of SUSY breaking models include scenarios such as gauge-mediated supersymmetry breaking (GMSB) [73–78] and anomaly-mediated supersymmetry breaking (AMSB) [79, 80].

R-parity

In general, it is possible to include baryon number and lepton number violating terms in the MSSM Lagrangian. However, such terms could be forbidden by imposing a symmetry called R -parity:

$$P_R \equiv (-1)^{3(B-L)+2s}, \quad (1.18)$$

where B is the baryon number, L is the lepton number, and s is the spin of the particle. Consequently, all SM particles have $P_R = +1$ and all SUSY partner particles have $P_R = -1$. The conservation of R -parity is motivated to prevent the decay of the proton, the lifetime of which is experimentally constrained to be $> 1.6 \times 10^{34}$ years [47]. Therefore, the MSSM is *defined* to conserve R -parity in this dissertation, as is done in many phenomenological studies of SUSY.

R -parity conservation requires an even number of SUSY particles for each interaction vertex in the theory. This leads to the following significant phenomenological consequences:

- In collider experiments using SM particles, SUSY particles must be produced in even numbers, usually in pairs.
- The lightest supersymmetric particle (LSP) cannot decay and must be stable.
- SUSY particles except the LSP eventually decay into states that contain an odd number of LSPs.

1.2.2 Solutions to the remaining problems of the Standard Model

Although SUSY was first motivated rather by theoretical aspects of QFT, the MSSM succeeds in giving fruitful solutions to the remaining problems of the SM.

Dark matter candidates from SUSY

As mentioned in Section 1.2.1, the lightest supersymmetric particle (LSP) in the MSSM is stable. If the LSP is electrically neutral, it interacts only weakly with ordinary matter. In this case, the LSP is a viable candidate of DM. There are two main candidates of LSP⁵: the lightest neutralino and the gravitino.

As will be discussed later in Sec. 1.2.3, electrically neutral components of bino, wino, and higgsino mix to form four mass eigenstates called neutralinos. The lightest neutralino is a leading candidate of WIMP DM. The mixing ratio of each component for the lightest neutralino largely depends on the parameters of the MSSM. In the case of bino-like DM, most models are excluded by the relic density constraint; bino-like DM has very small self interaction, leading to an early freeze-out and over-abundance of thermal relics. Despite that, there are scenarios which still survive, for example, the bino-stau coannihilation scenario, where the coannihilation of bino and the slightly heavier stau, the SUSY partner of the tau, contribute to annihilation of bino [82–84]. In the case of wino-like DM or pure higgsino-like DM, from the relic density constraint, the LSP mass is allowed up to 3 TeV

⁵The lightest sneutrino, SUSY partner of the neutrino, could also be a DM candidate, but is largely excluded by direct detection experiments [81]. Further discussion is therefore omitted here.

and 1.1 TeV, respectively. For lower masses, the LSP only accounts partially of all DM; other types of DM or non-thermal mechanisms must be introduced to explain all dark matter content [85–87]. Nevertheless, it is crucial to experimentally scrutinize all allowed mass regions, as it is more natural for the LSP to have a mass of $\mathcal{O}(100)$ GeV, considering the hierarchy problem.

On the other hand, the gravitino could be the LSP, which is the likely case for GMSB scenarios. However, models with gravitino LSP suffer from cosmological constraints called the “gravitino problem” [88–90]. As a result, it is favored that gravitino LSP should have mass of $\lesssim \mathcal{O}(10)$ eV.

Prospects of SUSY GUT

The running of gauge couplings in the MSSM strongly motivates the existence of GUT. Fig. 1.2 shows the running of the gauge couplings for the SM and the MSSM under renormalization group equations for SUSY breaking scale of $\mathcal{O}(\text{TeV})$. Although the three gauge couplings do not quite agree for the SM, they agree in the MSSM at $\Lambda_{\text{MSSM}} \sim 10^{16}$ GeV, indicating the possibility of supersymmetric GUT. Although partially excluded by proton decay lifetime experiments, viable models of SUSY GUT include SUSY $SU(5)$ and SUSY $SO(10)$.

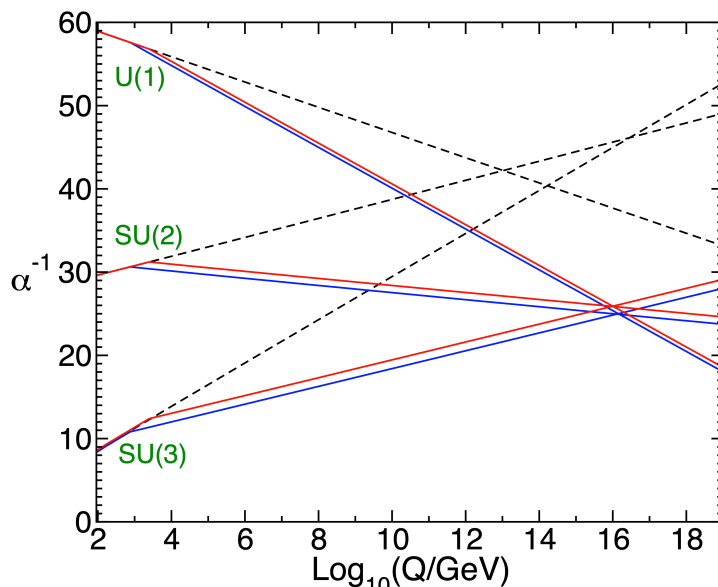


Figure 1.2: Running of inverse gauge couplings $\alpha_a^{-1}(Q)$ ($a = 1, 2, 3$) for the SM (dashed lines) and the MSSM (solid lines) using two-loop renormalization group equations [28]. For the MSSM, the common SUSY mass is varied between 750 GeV and 2.5 TeV, and $\alpha_3(m_Z)$ is varied between 0.117 and 0.120.

Solutions to the fine-tuning problem of the Higgs mass

One of the leading motivations of SUSY is its capability of solving the fine-tuning problem of the Higgs mass. In the SM, the most significant correction to the Higgs mass comes from the one-loop top quark diagram shown in Fig. 1.3a, represented as

$$\Delta m_H^2 = -\frac{|\lambda_t|^2}{8\pi^2} \Lambda^2 + \dots, \quad (1.19)$$

where Λ is the cutoff scale, and λ_t is the Yukawa coupling of the top quark. In models with SUSY, the one-loop scalar top (stop) diagram shown in Fig. 1.3b also contribute to the Higgs mass calculation:

$$\tilde{\Delta}m_H^2 = +2 \cdot \frac{\lambda_{\tilde{t}}}{16\pi^2} \Lambda^2 + \dots \quad (1.20)$$

Since, $\lambda_{\tilde{t}} = |\lambda_t|^2$ holds under SUSY, the quadratic divergences of Δm_H^2 and $\tilde{\Delta}m_H^2$ cancel out. Thus, the fine-tuning of parameters is unnecessary in SUSY, and the problem is solved. However, it is notable that soft SUSY breaking leads to the incomplete cancellations of the terms other than the quadratic term. SUSY breaking must occur near the TeV-scale, otherwise the remaining terms will come into effect, possibly reviving the fine-tuning problem.

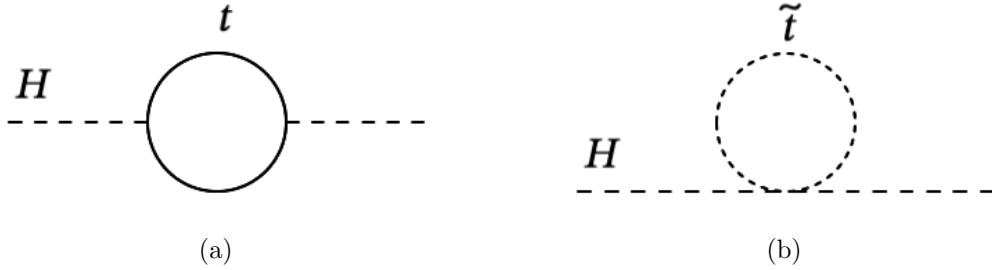


Figure 1.3: One-loop radiative corrections contributing to the Higgs mass calculation. (a) is from the top quark, which leads to quadratic divergences in the SM. (b) is the contribution from the scalar top (stop) in SUSY, which cancels contribution from (a).

1.2.3 The mass spectrum of the MSSM

This section gives a brief overview of the mass spectrum of the MSSM, necessary for understanding the phenomenological consequences and current experimental constraints.

Higgs sector

As mentioned in Sec. 1.2.1, the MSSM Higgs sector possesses two Higgs doublets: $H_u = (H_u^+, H_u^0)$ and $H_d = (H_d^0, H_d^-)$. Extracting the terms that contribute to electroweak symmetry breaking, the MSSM Higgs scalar potential is given by

$$\begin{aligned} V = & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\ & + \{b(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}\} \\ & + \frac{1}{8}(g_2^2 + g_Y^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2}g_2^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2, \quad (1.21) \end{aligned}$$

where g_2 and g_Y are the $SU(2)_L$ and $U(1)_Y$ gauge coupling constants, and μ is a Higgs parameter originating from the supersymmetric Lagrangian. The terms with $m_{H_u}^2, m_{H_d}^2$, and b are terms which contribute to Eq. (1.14). To realize electroweak symmetry breaking as done in the SM, H_u^0 and H_d^0 are both required to acquire non-zero VEVs:

$$v_{\text{SM}}^2 = v_u^2 + v_d^2 = \frac{2m_Z^2}{g_2^2 + g_Y^2}, \quad (1.22)$$

where we have defined

$$v_{u,d} \equiv \langle H_{u,d}^0 \rangle. \quad (1.23)$$

m_Z is the mass of the Z boson. By further defining

$$\tan \beta \equiv \frac{v_u}{v_d} \quad (1.24)$$

and imposing the conditions $H_u^+ = H_d^- = 0$ and $\partial V / \partial H_u^0 = \partial V / \partial H_d^0 = 0$, one obtains

$$\sin(2\beta) = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2} \quad (1.25)$$

$$m_Z^2 = \frac{|m_{H_u}^2 - m_{H_d}^2|}{\sqrt{1 - \sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2. \quad (1.26)$$

As a result of electroweak symmetry breaking, three of the eight real scalar degrees of freedom of the two Higgs doublets are absorbed as the longitudinal modes of the $SU(2)_L$ gauge bosons, leading to massive $W^\pm$ and Z bosons. The remaining five degrees of freedom emerge as the following scalar mass eigenstates: two CP-even neutral scalars h^0 and H^0 , one CP-odd neutral scalar A^0 , and two charged scalars $H^\pm$. The tree-level masses of these Higgs bosons are given by assuming that $v_{u,d}$ minimize the tree-level potential V and using Eq. (1.25) and Eq. (1.26):

$$m_{A^0}^2 = m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 \quad (1.27)$$

$$m_{h^0, H^0}^2 = \frac{1}{2} \left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2(2\beta)} \right) \quad (1.28)$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2, \quad (1.29)$$

where m_W is the mass of the $W^\pm$ bosons. h^0 is lighter than H^0 by convention and corresponds to the Standard Model Higgs boson H shown in Table 1.2.

Neutralinos and charginos

Electroweak symmetry breaking induces the mixing of higgsinos, winos, and binos. The four neutral components $\tilde{H}_u^0, \tilde{H}_d^0, \tilde{W}^0$, and $\tilde{B}$ mix to form four mass eigenstates called neutralinos, denoted by $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$). The charged components $\tilde{H}_u^\pm, \tilde{H}_d^\pm$, and $\tilde{W}^\pm$ mix to form two charged eigenstates called charginos, denoted by $\tilde{\chi}_i^\pm$ ($i = 1, 2$). By convention, the smaller the subscript, the lighter the mass: $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_3^0} < m_{\tilde{\chi}_4^0}$ and $m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^\pm}$.

The neutralino mass part of the Lagrangian can be written as

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^T \mathbf{M}_{\tilde{\chi}^0} \psi^0 + \text{c.c.}, \quad (1.30)$$

using the gauge-eigenstate basis $\psi^0 = (\tilde{H}_u^0, \tilde{H}_d^0, \tilde{W}^0, \tilde{B})$. The mass matrix is then

$$\mathbf{M}_{\tilde{\chi}^0} = \begin{pmatrix} 0 & -\mu & -s_\beta c_W m_Z & s_\beta s_W m_Z \\ -\mu & 0 & c_\beta c_W m_Z & -c_\beta s_W m_Z \\ -s_\beta c_W m_Z & c_\beta c_W m_Z & M_2 & 0 \\ s_\beta s_W m_Z & -c_\beta s_W m_Z & 0 & M_1 \end{pmatrix}, \quad (1.31)$$

where the abbreviations $s_\beta \equiv \sin \beta$, $c_\beta \equiv \cos \beta$, $s_W \equiv \sin \theta_W$, and $c_W \equiv \cos \theta_W$ have been introduced. θ_W is the SM weak mixing angle defined by $\tan \theta_W = g_Y/g_2$. M_2 and M_1 are the wino and bino mass parameters introduced in Sec. 1.2.1. The tree-level masses of the neutralinos are obtained by diagonalizing the mass matrix $\mathbf{M}_{\tilde{\chi}^0}$, hence, the neutralino masses and components strongly depend on SUSY parameters μ , M_2 , M_1 , and also $\tan \beta$.

The chargino mass part of the Lagrangian can similarly be written as

$$\mathcal{L}_{\text{chargino mass}} = -\frac{1}{2}(\psi^\pm)^T \mathbf{M}_{\tilde{\chi}^\pm} \psi^\pm + \text{c.c.}, \quad (1.32)$$

using the gauge-eigenstate basis $\psi^\pm = (\tilde{H}_u^+, \tilde{W}^+, \tilde{H}_d^-, \tilde{W}^-)$. The mass matrix could be written as

$$\mathbf{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} 0 & 0 & \mu & \sqrt{2}s_\beta m_W \\ 0 & 0 & \sqrt{2}c_\beta m_W & M_2 \\ \mu & \sqrt{2}c_\beta m_W & 0 & 0 \\ \sqrt{2}s_\beta m_W & M_2 & 0 & 0 \end{pmatrix}. \quad (1.33)$$

Since Eq. (1.33) takes a 2×2 block form, the tree-level chargino masses can easily be calculated as

$$m_{\tilde{\chi}_{1,2}^\pm}^2 = \frac{1}{2} \left(\mu^2 + M_2^2 + 2m_W^2 \mp \sqrt{(\mu^2 + M_2^2 + 2m_W^2)^2 - 4(\mu M_2 - m_W^2 \sin 2\beta)^2} \right). \quad (1.34)$$

Gluino

Contrary to the neutralino and chargino case, the gluino is a fermion with color and does not mix with any particles in the MSSM. Under the assumption of gauge unification at a certain high energy scale, the masses of gluino, wino, and bino also unify with a unified mass value of $m_{1/2}$. In that case, the gaugino mass parameters are related by

$$\frac{M_1}{g_1} = \frac{M_2}{g_2} = \frac{M_3}{g_3} = \frac{m_{1/2}}{g_{\text{GUT}}} \quad (1.35)$$

at any energy scale, where g_i ($i = 1, 2, 3$) are gauge couplings of $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$ groups⁶, and g_{GUT} is the unified gauge coupling. Accordingly, the gaugino mass parameters roughly satisfy the following relations at TeV scale:

$$M_3 : M_2 : M_1 \approx 6 : 2 : 1. \quad (1.36)$$

It is therefore natural to assume that the gluino is heavier than lighter neutralinos and charginos.

Squarks and sleptons

Although any scalars with the same quantum numbers could in general mix to form mass eigenstates, squarks and sleptons in the MSSM are expected to have less complicated mixing structures due to various experimental constraints regarding flavor-changing and CP-violating processes. It is popular to assume an idealized limit where the sfermion

⁶Note that g_1 here is different from g_Y by a constant factor: $g_1 = \sqrt{\frac{5}{3}}g_Y$

mass matrices in Eq. (1.15) are all proportional to a 3×3 identity matrix in generation space:

$$\mathbf{m}_{\mathbf{Q}}^2 = m_{Q_0}^2 \mathbf{1}, \quad \mathbf{m}_{\mathbf{u}}^2 = m_u^2 \mathbf{1}, \quad \mathbf{m}_{\mathbf{d}}^2 = m_d^2 \mathbf{1}, \quad \mathbf{m}_{\mathbf{L}}^2 = m_L^2 \mathbf{1}, \quad \mathbf{m}_{\mathbf{e}}^2 = m_e^2 \mathbf{1}. \quad (1.37)$$

Moreover, flavor-changing neutral current processes could further be suppressed by assuming that the trilinear coupling matrices in Eq. (1.15) are proportional to the corresponding Yukawa coupling matrices $\mathbf{y}_{\mathbf{u},\mathbf{d},\mathbf{e}}$, which could be approximated to have contributions only from the $(3, 3)$ generation components:

$$\begin{aligned} \mathbf{A}_{\mathbf{u}} = A_{u0} \mathbf{y}_{\mathbf{u}} &\approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_t \end{pmatrix}, \quad \mathbf{A}_{\mathbf{d}} = A_{d0} \mathbf{y}_{\mathbf{d}} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_b \end{pmatrix}, \\ \mathbf{A}_{\mathbf{e}} = A_{e0} \mathbf{y}_{\mathbf{e}} &\approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & A_\tau \end{pmatrix}. \end{aligned} \quad (1.38)$$

Under these assumptions and evolutions by renormalization group equations, all of the mass matrices in Eq. (1.37) can be approximated to a diagonal matrix indicating mass degeneracy of first and second generation sfermions. For example, the mass matrix of left-handed squarks can be approximately written as

$$\mathbf{m}_{\mathbf{Q}}^2 \approx \begin{pmatrix} m_{Q_{1,2}}^2 & 0 & 0 \\ 0 & m_{Q_{1,2}}^2 & 0 \\ 0 & 0 & m_{Q_3}^2 \end{pmatrix}. \quad (1.39)$$

Similar approximations can be applied to $\mathbf{m}_{\mathbf{u}}^2, \mathbf{m}_{\mathbf{d}}^2, \mathbf{m}_{\mathbf{L}}^2$, and $\mathbf{m}_{\mathbf{e}}^2$.

As a result of the large third-generation Yukawa couplings and trilinear couplings, the third generation sfermions could have different masses compared to their first- and second-generation counterparts. Moreover, there could be considerable mixing of left-handed and right-handed components for the third generation pairs: $(\tilde{t}_L, \tilde{t}_R), (\tilde{b}_L, \tilde{b}_R)$, and $(\tilde{\tau}_L, \tilde{\tau}_R)$. On the other hand, the first- and second- generation sfermions have negligible Yukawa couplings, resulting in nearly degenerate unmixed pairs: $(\tilde{u}_L, \tilde{c}_L), (\tilde{d}_L, \tilde{s}_L), (\tilde{u}_R, \tilde{c}_R), (\tilde{d}_R, \tilde{s}_R), (\tilde{e}_L, \tilde{\mu}_L), (\tilde{e}_R, \tilde{\mu}_R)$, and $(\tilde{\nu}_e, \tilde{\nu}_\mu)$.

Assuming that the sfermion masses are unified at GUT scale with a universal mass m_0 , the masses of the first- and second-generation sfermions could be written as

$$m_{Q_1}^2 = m_{Q_2}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_Q, \quad (1.40)$$

$$m_{u_1}^2 = m_{u_2}^2 = m_0^2 + K_3 + \frac{4}{9}K_1 + \Delta_u, \quad (1.41)$$

$$m_{d_1}^2 = m_{d_2}^2 = m_0^2 + K_3 + \frac{1}{9}K_1 + \Delta_d, \quad (1.42)$$

$$m_{L_1}^2 = m_{L_2}^2 = m_0^2 + K_2 + \frac{1}{4}K_1 + \Delta_L, \quad (1.43)$$

$$m_{e_1}^2 = m_{e_2}^2 = m_0^2 + K_1 + \Delta_e, \quad (1.44)$$

where K_i ($i = 1, 2, 3$) are contributions from the renormalization group running proportional to the gaugino mass parameters M_i . Δ_ϕ in each equation represents contributions from electroweak symmetry breaking, given by

$$\Delta_\phi = (T_{3\phi} - Q_\phi \sin^2 \theta_W) \cos(2\beta) m_Z^2, \quad (1.45)$$

where $T_{3\phi}$ and Q_ϕ are the third component of weak isospin and the electric charge of the left-handed chiral supermultiplet in which ϕ resides.

As for scalar top quarks or stops, the Lagrangian mass term is given by

$$\mathcal{L}_{\text{stop mass}} = - \begin{pmatrix} \tilde{t}_L^* & \tilde{t}_R^* \end{pmatrix} \mathbf{m}_{\tilde{t}}^2 \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (1.46)$$

where the mass matrix is written as

$$\mathbf{m}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{u_L} & v(A_t^* \sin \beta - \mu y_t \cos \beta) \\ v(A_t \sin \beta - \mu^* y_t \cos \beta) & m_{u_3}^2 + m_t^2 + \Delta_{u_R} \end{pmatrix}. \quad (1.47)$$

The mass matrix can then be diagonalized to give mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{t}} & -\sin^* \theta_{\tilde{t}} \\ \sin \theta_{\tilde{t}} & \cos^* \theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (1.48)$$

where the $\theta_{\tilde{t}}$ has been defined as the stop mixing angle. Due to renormalization group effects and significant mixing, $m_{Q_3}^2$ and $m_{u_3}^2$ in the diagonal elements of Eq. (1.47) are much smaller than corresponding parameters of first- and second-generation squarks, hence, $\tilde{t}_1$ is often the lightest squark in the MSSM.

Similar relations hold for sbottoms and staus with the following mass matrices:

$$\mathbf{m}_{\tilde{b}}^2 = \begin{pmatrix} m_{Q_3}^2 + \Delta_{dL} & v(a_b^* \cos \beta - \mu y_b \sin \beta) \\ v(a_b \cos \beta - \mu^* y_b \sin \beta) & m_{d_3}^2 + \Delta_{dR} \end{pmatrix}, \quad (1.49)$$

$$\mathbf{m}_{\tilde{\tau}}^2 = \begin{pmatrix} m_{L_3}^2 + \Delta_{eL} & v(a_\tau^* \cos \beta - \mu y_\tau \sin \beta) \\ v(a_\tau \cos \beta - \mu^* y_\tau \sin \beta) & m_{e_3}^2 + \Delta_{eR} \end{pmatrix}. \quad (1.50)$$

The degree of left-right mixing for sbottoms and staus largely depend on the value of $\tan \beta$. For small $\tan \beta$ roughly below 10, the mixing effect is minimal because of the smaller Yukawa couplings of bottom quark and tau lepton compared to that of the top quark. This results in a situation where $\tilde{b}_R, \tilde{\tau}_L, \tilde{\tau}_R$, and also $\tilde{\nu}_\tau$ are nearly mass degenerate with their first- and second- generation counterparts. However, $\tilde{b}_L$ could be substantially lighter than $\tilde{d}_L$ and $\tilde{s}_L$ due to effects induced by large top Yukawa coupling. For larger $\tan \beta$, significant left-right mixing effects lead to third-generation mass eigenstates $\tilde{b}_1$ and $\tilde{\tau}_1$, much lighter than their first- and second-generation counterparts. In this case, $\tilde{\nu}_\tau$ is also nearly mass degenerate with $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$.

Summary: theory to simplified models

Although the MSSM consists of a number of fundamental and soft SUSY breaking parameters, predictive models could be deduced by approximations consistent with various observations. By adopting approximations Eq. (1.38) and Eq. (1.39), the MSSM can be

Table 1.4: The list of parameters of pMSSM.

Parameter	Description
μ	Higgs/higgsino mass parameter
$\tan \beta$	Ratio of Higgs VEVs
m_{A^0}	Mass of CP-odd neutral Higgs
M_1	Bino mass parameter
M_2	Wino mass parameter
M_3	Gluino mass parameter
$m_{Q_{1,2}}$	First- and second-generation left-handed squark mass
m_{Q_3}	Third-generation left-handed squark mass
$m_{u_{1,2}}$	First- and second-generation right-handed up-type squark mass
m_{u_3}	Third-generation right-handed up-type squark mass
$m_{d_{1,2}}$	First- and second-generation right-handed down-type squark mass
m_{d_3}	Third-generation right-handed down-type squark mass
$m_{L_{1,2}}$	First- and second-generation left-handed slepton mass
m_{L_3}	Third-generation left-handed slepton mass
$m_{e_{1,2}}$	First- and second-generation right-handed slepton mass
m_{e_3}	Third-generation right-handed slepton mass
A_t	Top trilinear coupling
A_b	Bottom trilinear coupling
A_τ	τ trilinear coupling

reduced down to a more simple model called *phenomenological* MSSM (pMSSM), of which parameters are listed in Table 1.4.

Hints from spontaneous SUSY breaking could also give constraints to the MSSM. In the case of minimal supergravity model known as mSUGRA, the following relations are imposed at a renormalization scale $Q \approx 1.5 \times 10^{16}$ GeV:

$$M_1 = M_2 = M_3 = m_{1/2}, \quad (1.51)$$

$$m_Q^2 = m_u^2 = m_d^2 = m_L^2 = m_e^2 = m_0^2, \quad m_{H_u}^2 = m_{H_d}^2 = m_0^2, \quad (1.52)$$

$$\mathbf{A}_{\mathbf{u,d,e}} = A_0 \mathbf{Y}_{\mathbf{u,d,e}}, \quad (1.53)$$

$$b = B_0 \mu. \quad (1.54)$$

Parameters B_0 and μ can be reduced to $\tan \beta$ and $\text{sgn}(\mu)$ by requiring electroweak symmetry breaking. Fig. 1.4 shows the running of mass parameters in mSUGRA. There are also models which relax the Higgs mass constraint in Eq. (1.52), based on the reasoning that Higgs mass universality with m_0 does not follow any fundamental principles. These scenarios are known as Non-Universal Higgs Mass (NUHM) models. mSUGRA and NUHM models only have five to seven parameters and have been practically used as target benchmark models for experimental searches. It is worthwhile to note that mSUGRA scenarios typically predict the LSP to be bino-like, whereas NUHM scenarios often predict higgsino-like LSP.

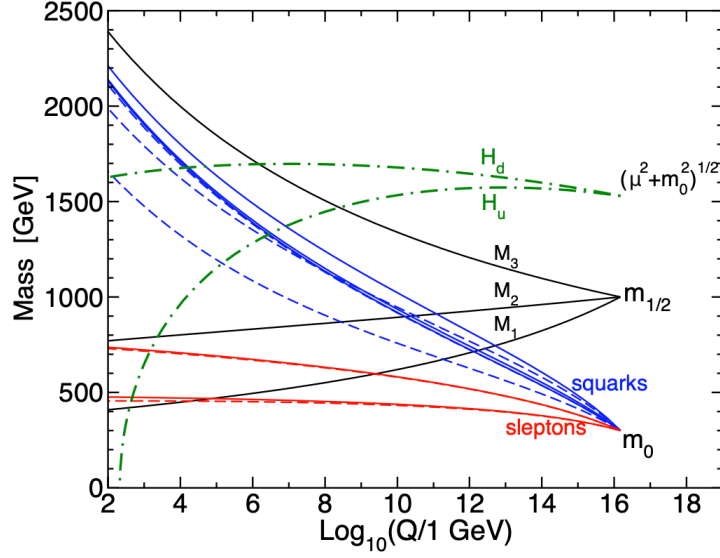


Figure 1.4: Renormalization group evolution of mass parameters in mSUGRA, assuming unification at $Q \approx 1.5 \times 10^{16}$ GeV [28]. The parameter values used for the illustration are $m_0 = 300$ GeV, $m_{1/2} = -A_0 = 1000$ GeV, $\tan \beta = 15$, and $\text{sgn}(\mu) = +$. $(\mu^2 + m_{H_u}^2)^{1/2}$ appearing in the Higgs potential Eq. (1.21) runs negative and induces electroweak symmetry breaking. The dashed lines for sfermions represent third generation mass parameters, while the solid lines represent first- and second-generation mass parameters.

1.2.4 Experimental constraints

This section highlights the various experimental constraints to SUSY, with focus on the MSSM.

Constraints from the Standard Model Higgs mass

The observed Higgs mass of 125 GeV gives a stringent constraint on the MSSM. From Eq. (1.28), one sees that at tree-level,

$$m_{h^0} < m_Z |\cos(2\beta)| < 91.2 \text{ GeV}, \quad (1.55)$$

which is far below the observed mass. Radiative corrections to the Higgs mass mainly from top and stop loops, give positive contributions, which in principle, are enough to accomodate the observed mass. The approximate one-loop correction is given by

$$\Delta(m_{h^0}^2) = \frac{3m_t^2}{4\pi^2 v^2} \left\{ \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right) \right\}, \quad (1.56)$$

where $m_{\tilde{t}} \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$ is the general stop mass, and $X_t \equiv A_t - \mu \cot \beta$ is the stop mixing parameter [91]. For this to be consistent with the observed Higgs mass, the stops must be much heavier than $\mathcal{O}(1 \text{ TeV})$ or the stop mixing must be significantly large as shown in Fig. 1.5.

Constraints from collider search experiments

The most “direct” constraints come from high-energy collider searches, performed by ATLAS and CMS collaborations at the LHC. Fig. 1.6 shows the production cross sections of various SUSY processes at the LHC.

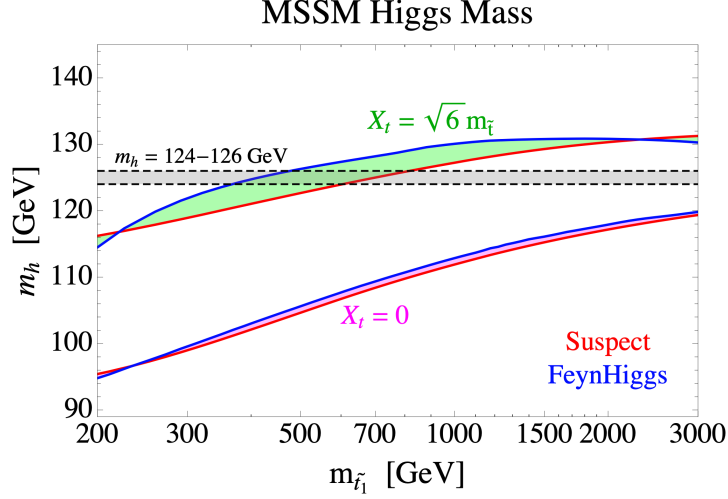


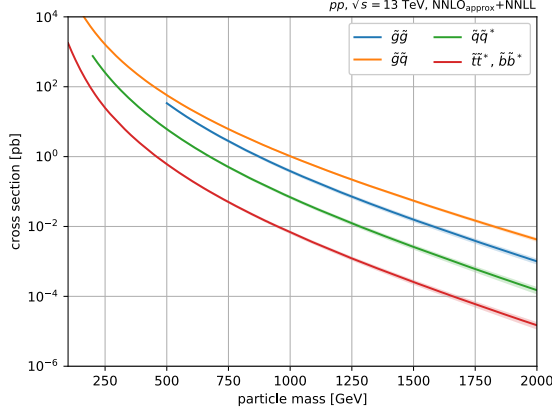
Figure 1.5: The Higgs mass in the MSSM as a function of the lightest stop mass $m_{\tilde{t}_1}$ [91]. The red(blue) solid lines show the values computed by Suspect(FeynHiggs). The upper lines show results with maximal stop mixing $X_t = \sqrt{6}m_{\tilde{t}}$, and the lower lines show results with minimal stop mixing $X_t = 0$.

Gluinos Gluino has high production cross section at the LHC and has been actively searched for by ATLAS and CMS experiments. Fig. 1.7 shows the exclusion limits for gluinos set by ATLAS and CMS experiments. Gluino searches are usually performed by searching for various decay products from the gluino decaying to the LSP, on top of an energetic jet and high missing transverse momentum. Gluinos with masses up to about 2.4 TeV have been already excluded, depending on the lightest neutralino mass.

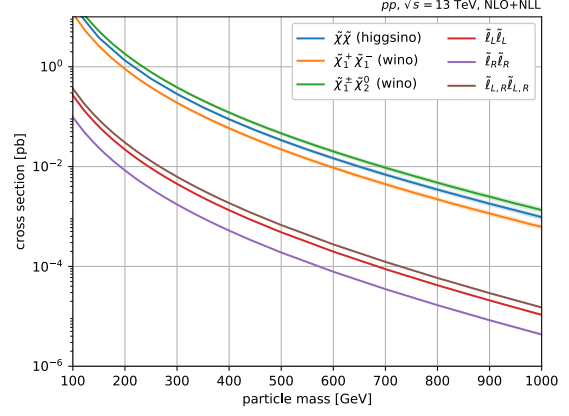
Squarks Squarks have also been actively searched by ATLAS and CMS experiments due to their high production cross sections at LHC. Searches for squarks are performed separately for third-generation and first/second-generation components, because third-generation squarks tend to be lighter than their first- and second-generation counterparts, as explained in Section 1.2.3. Fig. 1.8 shows exclusion limits for first- and second-generation squarks set by ATLAS and CMS experiments. Searches for squarks are usually performed with strategies similar to those of gluino searches, by searching for various decay products from the squarks decaying to the LSP, on top of an energetic jet and high missing transverse momentum. First- and second-generation squarks with masses up to about 1.8 TeV have been already excluded, depending on the lightest neutralino mass.

Fig. 1.9 shows exclusion limits for third-generation squarks (stops) set by ATLAS and CMS experiments. Stops with masses up to 1.3 TeV have been already excluded, depending on the lightest neutralino mass, ranging up to about 700 GeV. Limits on stop is less stringent compared to those of first- and second-generation squarks, since their production cross sections are much smaller as shown in Fig. 1.6a.

Electroweak sector Although production cross sections of electroweak SUSY particles (bino, winos, higgsinos, and sleptons) at the LHC are much smaller than those of strong SUSY particles, ATLAS and CMS experiments currently lead the SUSY searches targeting the electroweak sector. However, for some parameter regions, results from LEP2 experiments still hold the best results.

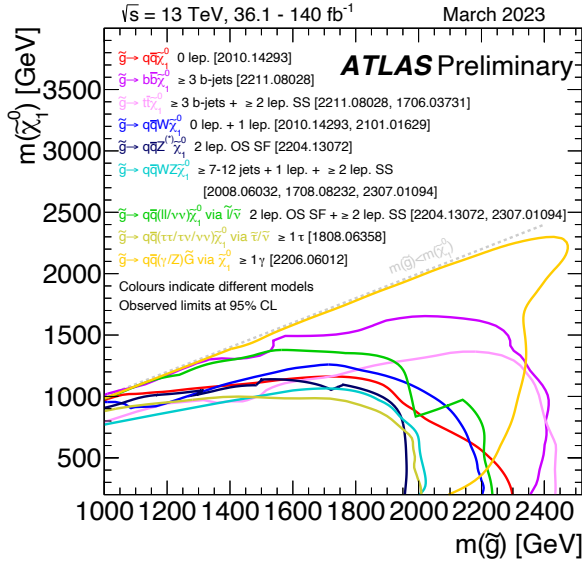


(a) Strong production processes

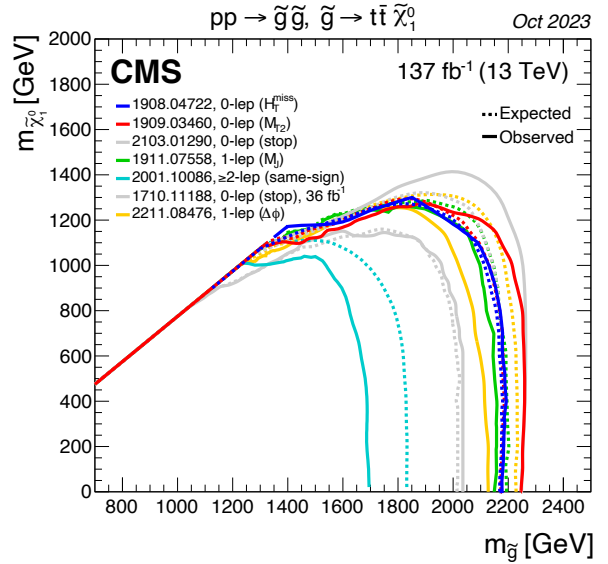


(b) Electroweak production processes

Figure 1.6: Production cross sections of SUSY processes at the LHC [92] for $\sqrt{s} = 13$ TeV.

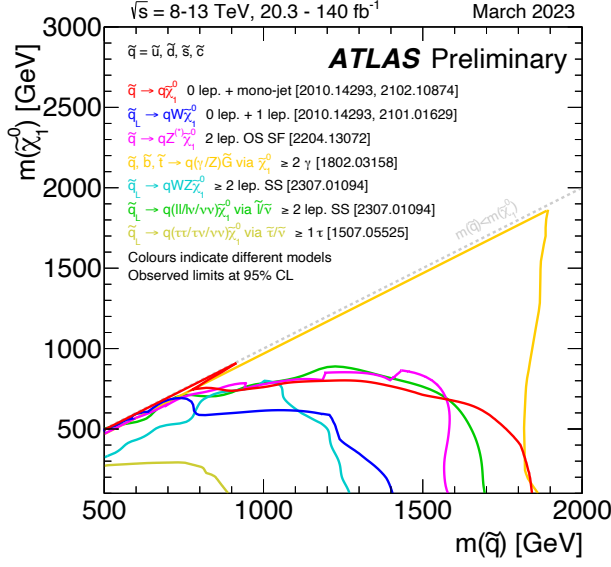


(a) Constraints by ATLAS

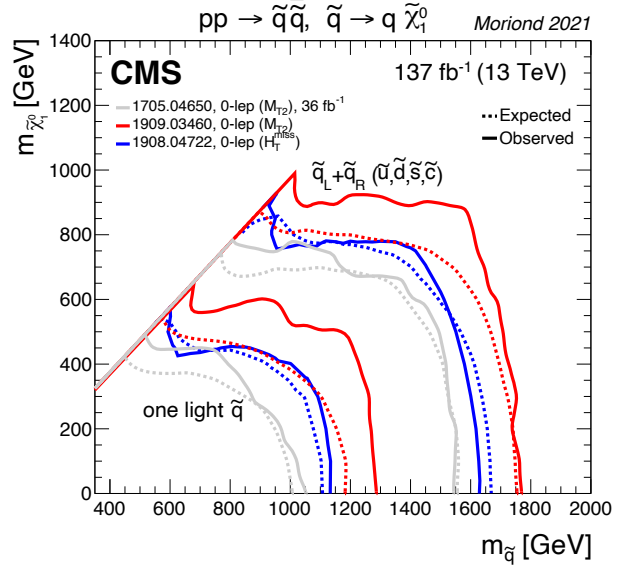


(b) Constraints by CMS

Figure 1.7: Constraints on gluino by ATLAS and CMS experiments in the (gluino, lightest neutralino) mass plane [93, 94]. The limits by ATLAS show search results for various decay channels, whereas the limits by CMS only show results for $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ decay channel. CMS results for other channels can be found in Reference [94].

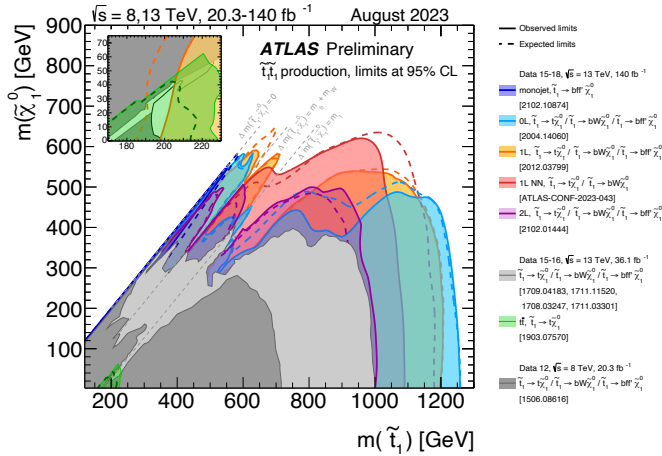


(a) Constraints by ATLAS

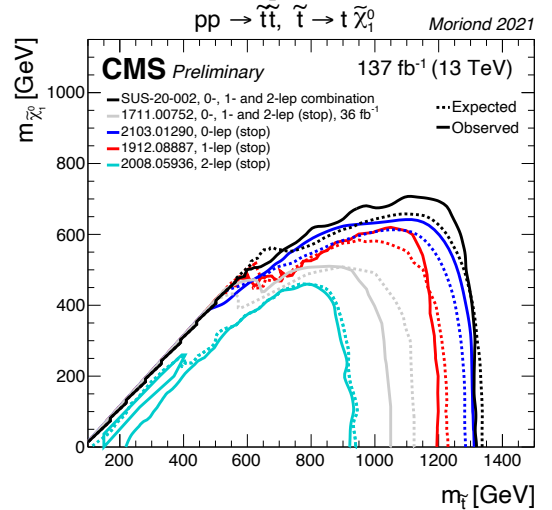


(b) Constraints by CMS

Figure 1.8: Constraints on first- and second-generation squarks by ATLAS and CMS experiments in the (squark, lightest neutralino) mass plane [93, 94]. The limits by ATLAS show search results for various decay channels, whereas the limits by CMS only show results for $q̃ \rightarrow q\tilde{\chi}_1^0$ decay channel. CMS results for other channels can be found in Reference [94].



(a) Constraints by ATLAS



(b) Constraints by CMS

Figure 1.9: Constraints on third-generation squarks (stops) by ATLAS and CMS experiments in the (stop, lightest neutralino) mass plane [93, 94]. The limits by ATLAS show search results for various decay channels, whereas the limits by CMS only show results for $t̃ \rightarrow t\tilde{\chi}_1^0$ decay channel. CMS results for other channels can be found in Reference [94].

SUSY scenarios with bino-like LSP and wino-like NLSP have been most actively explored, as they present signatures which are more accessible compared to other scenarios. Signals for such scenarios are expected to leave multiple leptons and high missing transverse momentum in the final states. Fig. 1.10 shows exclusion limits for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$, mainly targeting the bino-like LSP and wino-like NLSP scenario. For this scenario, winos with masses of up to about 1.4 TeV and bino with mass of up to about 800 GeV have been excluded.

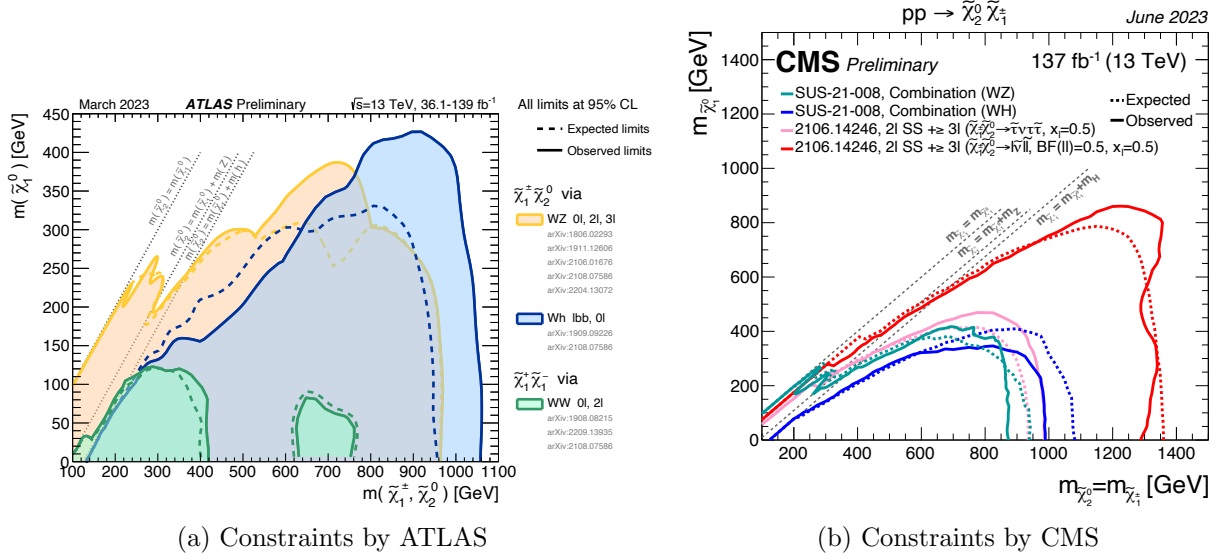
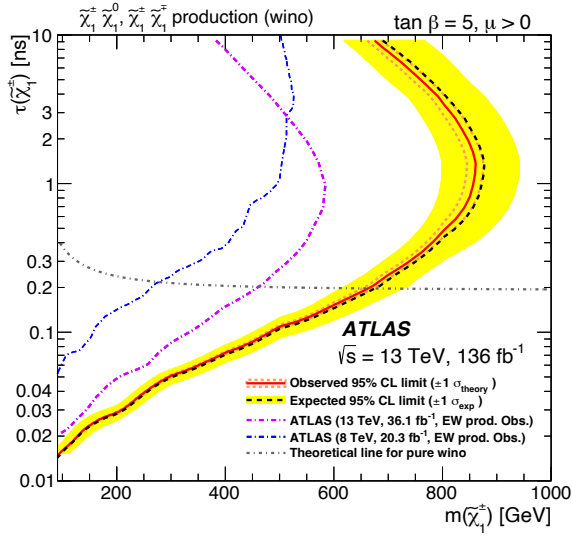


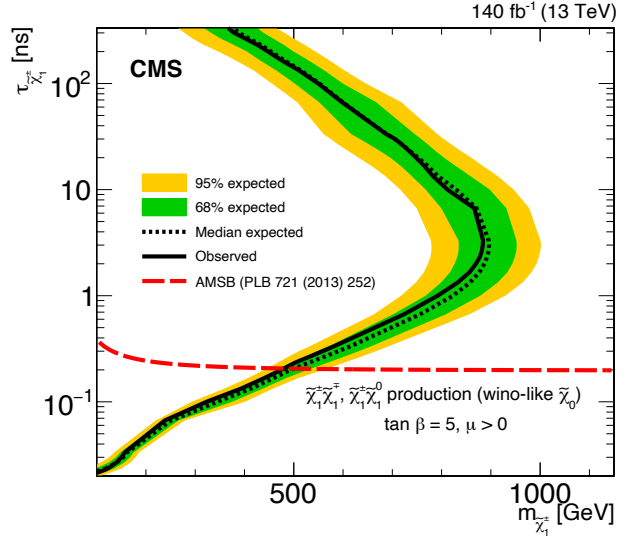
Figure 1.10: Constraints on $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ by ATLAS and CMS experiments [93, 94]. The limits by ATLAS show search results only for decays via $W/Z/H$, whereas the limits by CMS also include intermediate decays with sleptons. ATLAS results for other channels can be found in Reference [93].

Scenarios with wino-like LSP are expected to present “disappearing track” signatures, which are produced by long-living lightest chargino decaying to the lightest neutralino. Fig. 1.11 shows exclusion limits for the wino LSP scenario by ATLAS and CMS experiments, targeting disappearing tracks. Pure winos have been excluded up to masses of 650 GeV.

Scenarios with higgsino-like LSP have been explored using several strategies, depending on the mass splitting values within the higgsino-like triplet $(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0)$. Fig. 1.12 shows the newest exclusion limits on higgsino-like LSP scenarios set by ATLAS. For previous searches, multi-lepton searches targeting soft leptons emitted from higgsino decays have searched regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ larger than about 1.5 GeV. Disappearing track searches have probed regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ smaller than about 400 MeV, excluding pure higgsinos with masses of up to about 200 GeV. The newest displaced track search has successfully searched the region in between, excluding the regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ smaller than about 1 GeV, for masses up to about 170 GeV. However, the regions between those searched by the displaced track search and multi-lepton searches have not yet been probed by the LHC, leaving the limit by the LEP2 experiments the most stringent. It is worthwhile to mention here that **the purpose of the research described in this dissertation is to search for higgsino-like LSP scenarios in this regime with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ of about 1–1.5 GeV.**



(a) Constraints by ATLAS



(b) Constraints by CMS

Figure 1.11: Constraints on wino LSP by ATLAS and CMS experiments [95, 96].

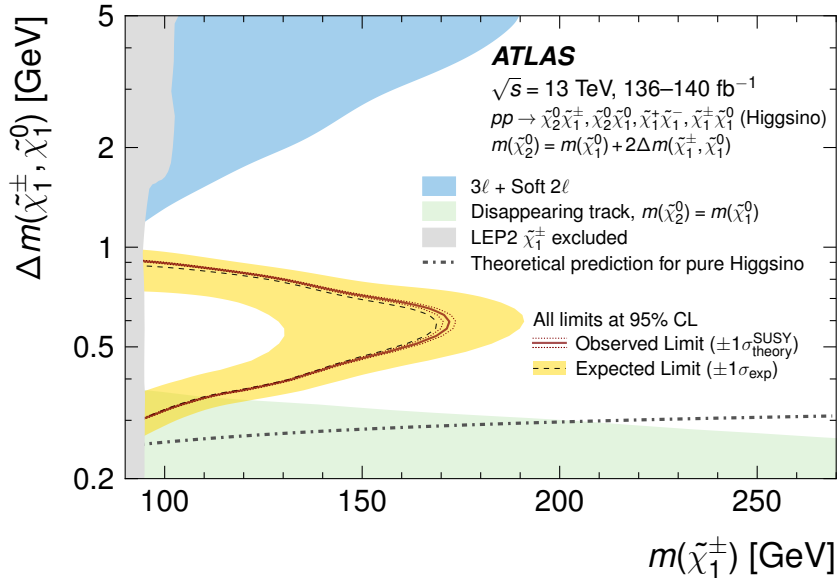


Figure 1.12: Recent experimental constraints by ATLAS on the higgsino-like LSP scenarios [97]. The combination of the soft 2L and 3L analysis (blue) probes mass splittings larger than about 1.5 GeV while the disappearing track analysis (light green) is sensitive to the ultra-compressed regime with mass splittings of only several hundred MeV. New limits have been recently set by the displaced track analysis, probing the regions in between, with mass splittings below 1 GeV.

Direct production of sleptons have also been searched at the LHC. Fig. 1.13 shows the exclusion limits on direct slepton production set by ATLAS. Searches for sleptons have been commonly performed by focusing on leptons emitted from the $\tilde{l} \rightarrow l\tilde{\chi}_1^0$ decay. Similar to other SUSY searches, events with an energetic jet and high missing transverse momentum become significant for regimes where the slepton and the LSP have compressed mass spectra. First- and second-generation sleptons (selectrons and smuons) have been excluded up to masses of about 700 GeV, and third-generation sleptons (staus) have been excluded up to masses of about 450 GeV, depending on the lightest neutralino mass.

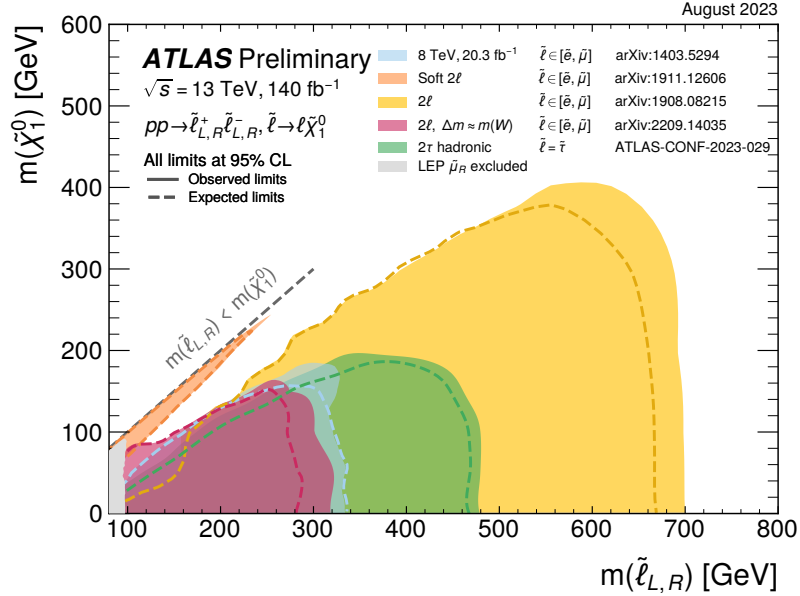


Figure 1.13: Recent experimental constraints by ATLAS on direct production of sleptons [93]. Searches for sleptons have been performed by focusing on leptons emitted from the $\tilde{l} \rightarrow l\tilde{\chi}_1^0$ decay.

BSM Higgs As described in Section 1.2.3, the MSSM introduces another Higgs doublet, resulting in four BSM Higgs bosons. Hence, experimental constraints on the BSM Higgs could also be interpreted as additional constraints on the MSSM. Since BSM Higgs are expected to be much heavier than the SM Higgs boson, ATLAS and CMS lead the searches for them. The Higgs sector parameters of the MSSM can be reduced down to m_{A^0} and $\tan\beta$ as shown in Table 1.3, and search results are often summarized in a 2D plane of those parameters. Fig. 1.14 shows the exclusion limits on BSM Higgs in the hMSSM benchmark scenario [98–100], set by ATLAS and CMS. Regions with $\tan\beta > 10$ have already been largely excluded for m_{A^0} ranging from 1–2 TeV. Regions with smaller $\tan\beta$ have looser limits; only up to about $m_{A^0} = 700$ –800 GeV have been excluded, depending on $\tan\beta$.

Constraints from dark matter experiments

As explained in Section 1.2.2, MSSM scenarios with R-parity conservation is expected to introduce dark matter candidates. Therefore, experimental constraints on DM observations and searches give crucial hints to MSSM phenomenology. Here, particular emphases

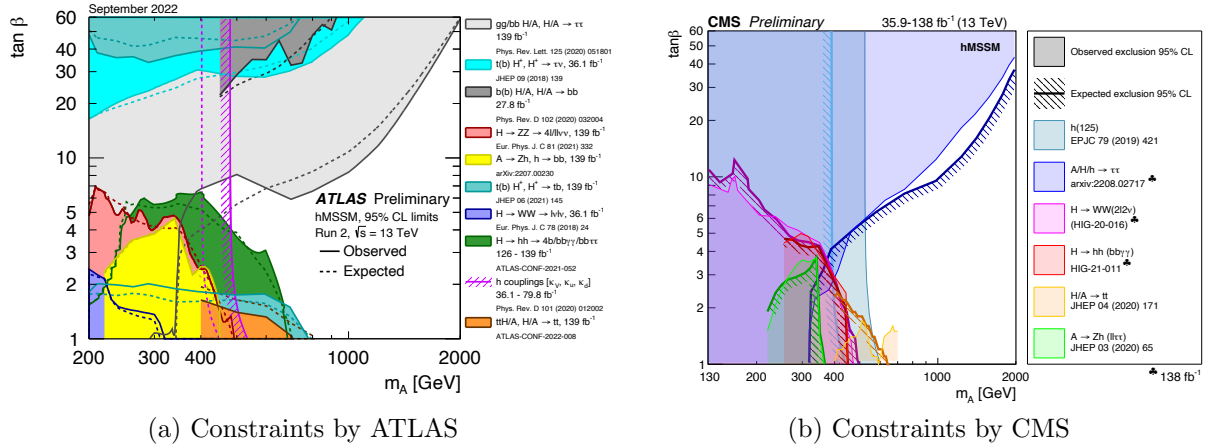


Figure 1.14: Constraints on BSM Higgs by ATLAS and CMS experiments [101, 102] in the hMSSM benchmark scenario.

will be put on scenarios having the lightest neutralino as the LSP and a WIMP DM candidate.

Relic density constraint Recent observations indicate the DM relic density to be $\Omega_{\text{DM}} h^2 \simeq 0.12$ [13], as described in Section 1.1.2. This value sets a very stringent constraint on the LSP mass, with the assumption that all dark matter content consists only of the LSP. However, in principle, it is possible that the LSP only accounts for only a fraction of the DM content. In this case, the relic density constraint becomes rather loose; LSP masses below that satisfying the relic density equality are allowed.

Fig. 1.15 shows the expected relic density of the neutralino as a function of the LSP neutralino mass, for each neutralino type. Bino-like LSP is mostly excluded in terms of relic density, as it results in overabundance due to its small annihilation cross sections. On the other hand, wino-like LSP and higgsino-like LSP have relic densities smaller than the experimental constraint; up to 3 TeV and 1.1 TeV is allowed, respectively. Therefore, in terms of dark matter relic density, SUSY scenarios with wino-like LSP and higgsino-like LSP are generally more viable than those with bino-like LSP. However, some bino-like LSP scenarios are still possible; scenarios where the bino coannihilates with other SUSY particles (e.g. staus) could realize smaller relic densities [103].

Constraints from direct detection experiments Another constraint on WIMP dark matter comes from direct detection experiments, which search for WIMP-nucleon interaction. The most stringent limit on spin-independent WIMP-nucleon cross section (σ_{SI})⁷ is currently set by the LUX-ZEPLIN (LZ) experiment [105]. For WIMP masses of 100 GeV to 1 TeV, σ_{SI} down to $2 \times 10^{-47} \text{ cm}^2$ to $2 \times 10^{-46} \text{ cm}^2$ have already been excluded.

For the projection of direct detection results to constraints on the LSP neutralino, one must scale the WIMP-nucleon cross section with the expected relic abundance of the LSP, because it may be the case that the LSP only accounts for a fraction of currently existing dark matter content. Fig. 1.17 shows the scaled relic density of higgsino-like

⁷There are also limits on spin-dependent WIMP-nucleon cross section (σ_{SD}), but they are less stringent compared to limits on σ_{SI} , so the discussion is omitted here.

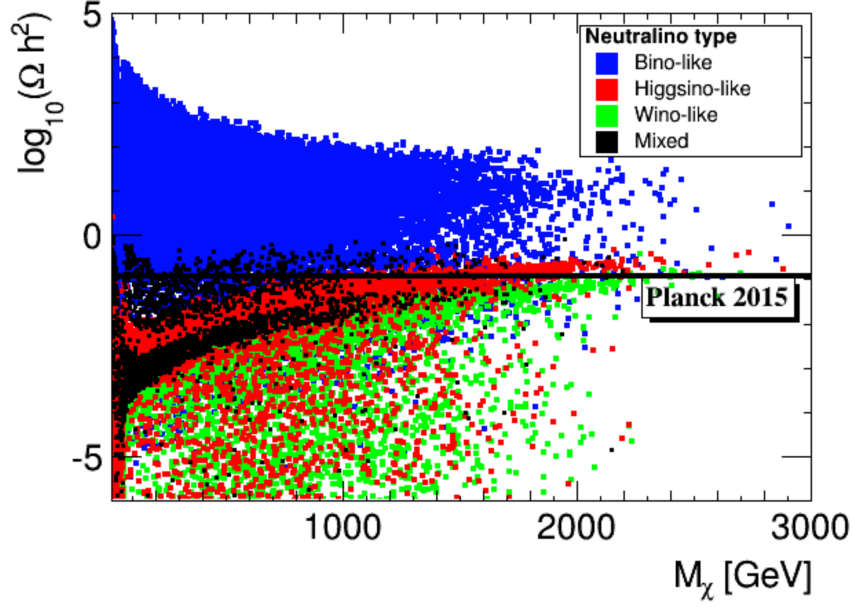


Figure 1.15: Neutralino relic density as a function of the LSP neutralino mass [104]. The neutralino is referred to as bino-/wino-/higgsino-like when it is composed of at least 90% bino/wino/higgsino component, respectively, or mixed state otherwise. Relic density results by Planck is shown as a black line for comparison.

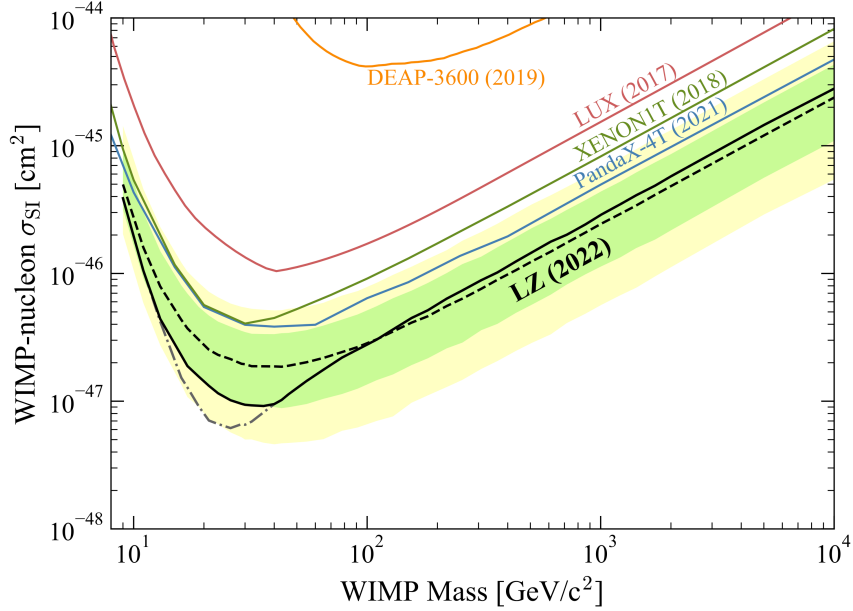


Figure 1.16: Constraint on the spin-independent WIMP-nucleon cross section set by the LZ experiment [105]. The solid black line shows the 90% confidence limit. For WIMP mass of 100 GeV, $\sigma_{\text{SI}} \gtrsim 2 \times 10^{-47} \text{ cm}^2$ has been excluded.

LSP calculated under the mSUGRA scenario, compared with limits from direct detection experiments. By comparing this with Fig. 1.16, one can see that higgsino-like LSP is only partially excluded. In scenarios with wino-like or bino-like LSP, σ_{SI} is typically smaller and are less constrained by direct detection experiments.

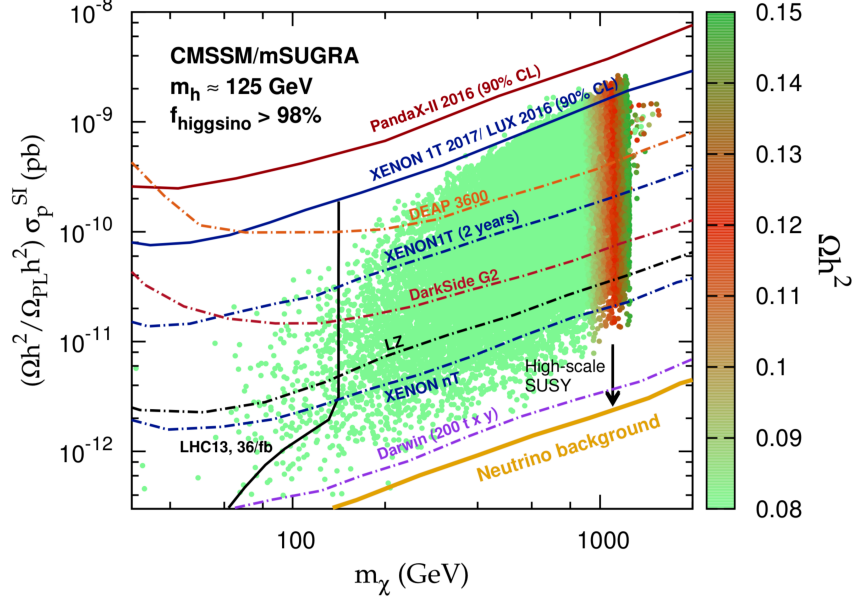


Figure 1.17: Spin-independent WIMP-nucleon cross section for higgsino-like LSP, as a function of LSP neutralino mass [106]. The WIMP-nucleon cross section has been scaled by the relic density fraction. Solid lines show observed limits, whereas dot-dashed lines show projected reach of each experiment, as of February 2018.

1.3 Target scenario and search strategy

The search introduced in this dissertation focuses on MSSM scenarios having higgsino-like LSP. In this section, details of the target scenario and analysis strategies are presented.

1.3.1 Target scenario

MSSM with higgsino-like LSP are one of the most viable candidates of SUSY and BSM scenarios, from both theoretical and experimental perspectives. LSP neutralino with a mass of $\mathcal{O}(100)$ GeV is a perfect candidate for WIMP dark matter; the options are bino-like, wino-like, and higgsino-like LSP. Bino-like LSP is mostly excluded due to its small annihilation cross section and overabundance. Wino-like LSP has already been actively searched with available LHC data and is excluded up to mass of about 800 GeV, although depending on the mass splitting. However, higgsino-like LSP has only been searched up to mass of about 200 GeV with currently available LHC data as shown in Fig. 1.12. For some mass splitting values, limits from LEP2 experiments remain the most stringent, excluding up to mass of only about 90 GeV. Since solutions to the hierarchy problem favor SUSY particles to be relatively light ($\mathcal{O}(100)$ GeV), it is highly crucial to search for higgsino-like LSP in the unfathomed mass regions.

MSSM scenarios with higgsino-like LSP are also barely constrained from searches for other SUSY particles described in Section 1.2.4. Higgsino-like LSP scenarios have typical mass parameter relations of $M_1, M_2 \gg \mu$, indicating large gluino mass according to Eq. (1.36). Generally, masses of squarks, sleptons, and BSM Higgs could also be much larger than those excluded by various searches at the LHC. Therefore, MSSM scenarios with higgsino-like LSP have not been excluded by any indirect experimental constraints and currently remain as one of the most viable candidates of physics beyond the SM.

In scenarios with higgsino-like LSP, in addition to the lightest neutralino $\tilde{\chi}_1^0$, the lightest chargino $\tilde{\chi}_1^\pm$ and the next-to-lightest neutralino $\tilde{\chi}_2^0$ become higgsino-like. Thus, the higgsino triplet $(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ usually have compressed mass spectra. In the target scenario of this search, the mass of $\tilde{\chi}_1^\pm$ is assumed to be exactly in the middle between the masses of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for simplicity:

- $m(\tilde{\chi}_2^0) > m(\tilde{\chi}_1^\pm) > m(\tilde{\chi}_1^0)$,
- $m(\tilde{\chi}_1^\pm) = \frac{1}{2} \{m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)\}$.

In particular, the search presented in this dissertation aims to probe regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ of about 1–1.5 GeV (or $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of about 2–3 GeV), which have not yet been explored by experiments at the LHC.

1.3.2 Previous searches

As stated previously in Section 1.2.4, various high-energy collider searches have targeted higgsino-like LSP scenarios. Fig. 1.18 summarizes the existing experimental constraints on the simplified higgsino model set by ATLAS.

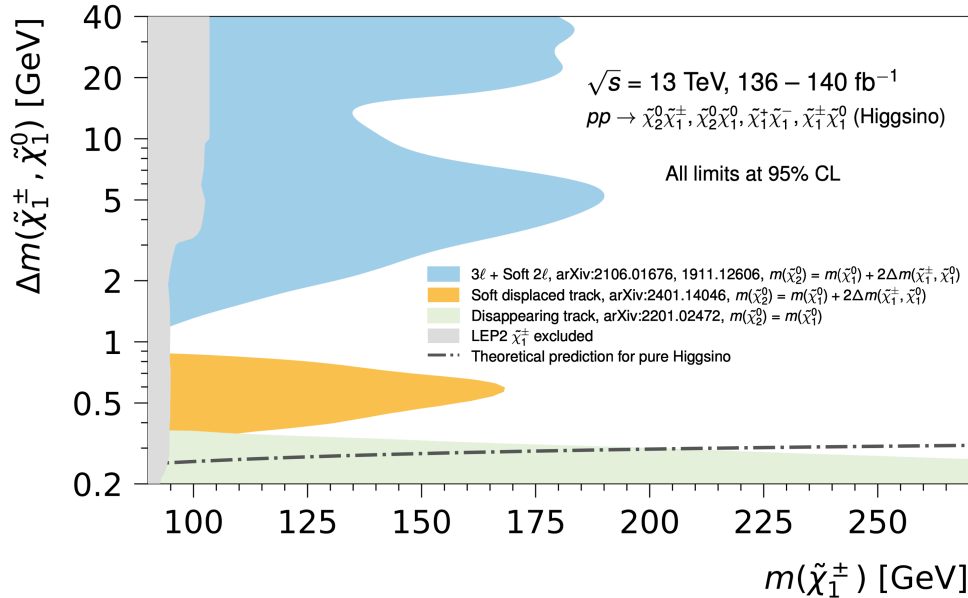


Figure 1.18: Existing experimental constraints on the simplified higgsino model under consideration, set by ATLAS.

Results from LEP2 experiments The gray area in Fig. 1.18 shows the excluded regions by the LEP2 experiments (ALEPH, DELPHI, L3, and OPAL). The LEP2 collided electrons and positrons at $\sqrt{s} = 208\text{--}209$ GeV, and all four experiments have searched for higgsinos. In the compressed mass region of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.2\text{--}3$ GeV, soft events with an Initial State Radiation (ISR) photon were targeted. $m(\tilde{\chi}_1^\pm) > 92.4$ GeV has been excluded at 95% C.L. for all mass splitting values by combining the results by the four experiments. For $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ of about 1 GeV, this limit has remained the most stringent.

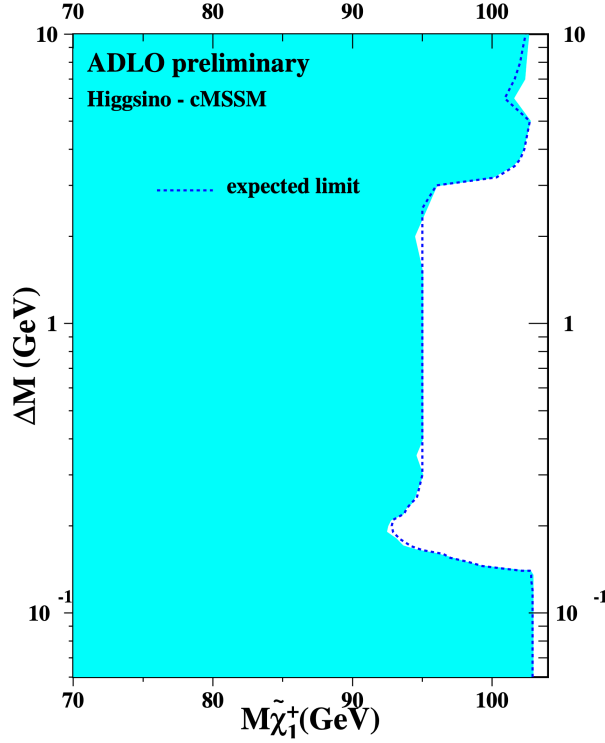


Figure 1.19: Experimental constraints on higgsinos set by LEP2 experiments [107]. $m(\tilde{\chi}_1^\pm) > 92.4$ GeV has been excluded at 95% C.L. for all mass splitting values.

Multi-lepton searches The blue area in Fig. 1.18 shows the excluded regions by the multi-lepton searches (3L and soft 2L) by ATLAS. Fig. 1.20 shows example diagrams of processes targeted by the multi-lepton searches. The 3L search targets $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair production and requires three leptons emitted from $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell^\pm \nu$ and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^\pm \ell^\mp$ decays, on top of high missing transverse momentum. The soft 2L search targets both $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair productions and searches for two leptons emitted from the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^\pm \ell^\mp$ decay.

Although the soft 2L search has the power to probe regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ of a few GeV, its sensitivity drops significantly for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 2$ GeV. This is because the electron and muon identification efficiencies in the ATLAS experiment drop significantly for low transverse momentum (p_T), as shown in Fig. 1.21. The electron and muon identification methods have a p_T threshold of 4.5 GeV and 3 GeV, respectively. Hence, the soft 2L search has also targeted events with one identified lepton and one unidentified isolated track to probe into regions with very small mass splittings.

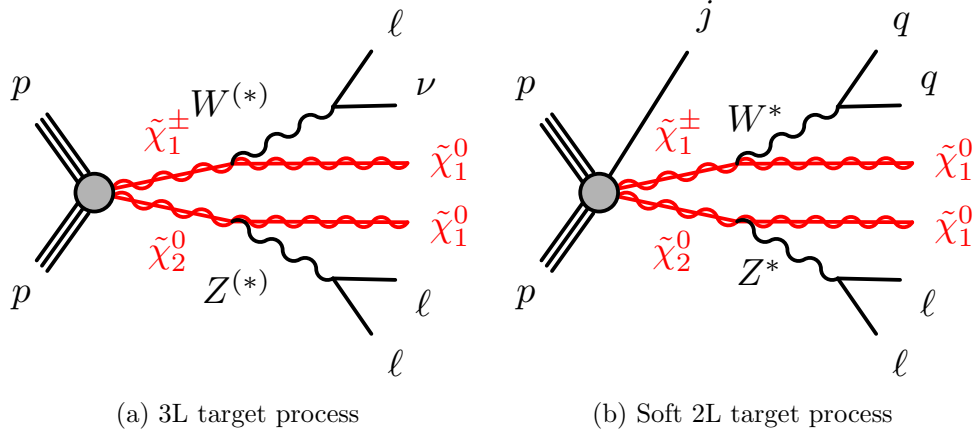


Figure 1.20: Example diagrams of processes targeted by multi-lepton searches by ATLAS [108, 109].

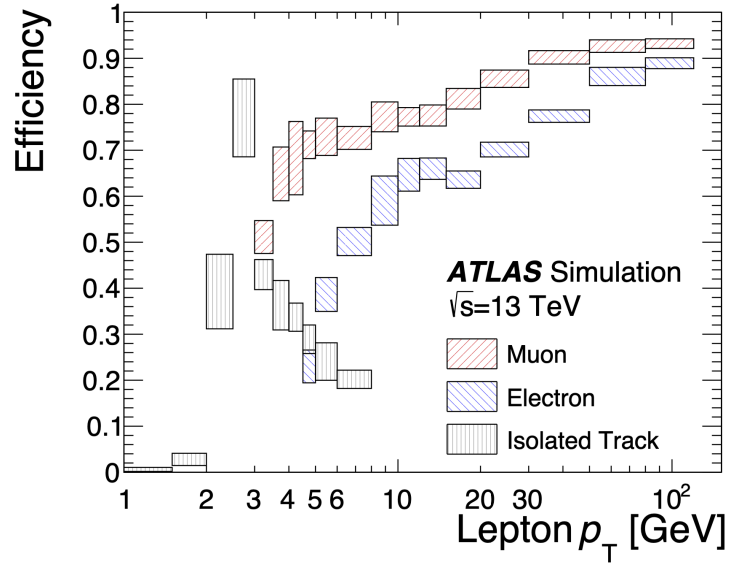


Figure 1.21: Signal lepton efficiencies for the soft 2L search in ATLAS [109]. In addition to standard leptons (electrons and muons), unidentified isolated tracks have been utilized to search soft leptons originating from the higgsino decay.

Disappearing track search The light green area in Fig. 1.18 shows the excluded regions by the disappearing track search by ATLAS. Fig. 1.22 shows an example diagram of the process targeted by the disappearing track search. For very low mass splittings of only several hundred MeV, the $\tilde{\chi}_1^\pm$ becomes long-lived and could traverse the inner layers of the ATLAS Inner Detector before decaying into an extremely soft pion, which is not reconstructed. This gives rise to a specific signature referred to as a “disappearing track”: the track of the $\tilde{\chi}_1^\pm$ is visible in the first few tracking layers but vanishes in the outer tracking layers. The search is sensitive to regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ smaller than 400 MeV and has excluded pure higgsinos with masses up to about 200 GeV.

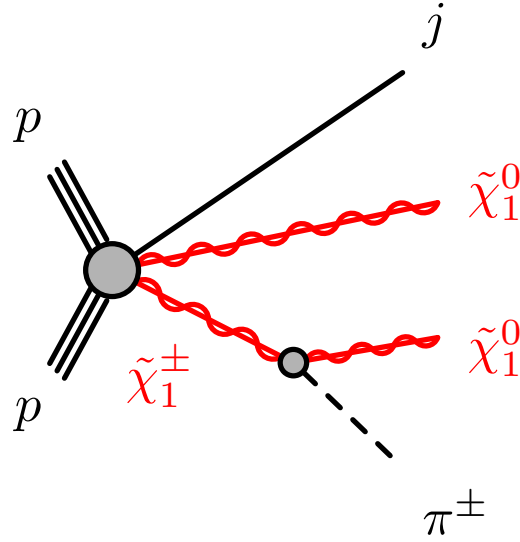


Figure 1.22: An example diagram of the process targeted by the disappearing and displaced track searches by ATLAS [95].

Displaced track search The yellow area in Fig. 1.18 shows the excluded regions by the displaced track search by ATLAS. The displaced track search also targets event topologies shown in Fig. 1.22. In the region between those searched by the multi-lepton searches and the disappearing track search, the $\tilde{\chi}_1^\pm$ has a notable lifetime and can fly up to several millimeters before decaying into $\tilde{\chi}_1^0$ and a charged pion. In this case, the charged pion can be reconstructed as a soft, isolated, and displaced track. The displaced track search targeting such signatures has excluded higgsino-like $\tilde{\chi}_1^\pm$ with masses up to 165 GeV and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ between 300 and 900 MeV, dependent on the $\tilde{\chi}_1^\pm$ mass.

1.3.3 Analysis strategy

The search presented in this dissertation targets $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ higgsino pair production from proton-proton collisions. Fig. 1.23 shows the branching ratios of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. The branching ratio of $\tilde{\chi}_2^0$ decaying leptonically to $\tilde{\chi}_1^0$ is approximately 5% for e^+e^- and $\mu^+\mu^-$, respectively. Although the branching ratios are relatively small, targeting this opposite-charge same-flavor lepton pair is a valid search method, as the features of the di-lepton system can be exploited to achieve sufficient background suppression. However, for mass splittings of a few GeV, the leptons from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ decay only have

transverse momentum (p_T) of a few GeV. As shown in Fig. 1.21, many of these leptons elude the standard lepton identification methods in ATLAS, which have p_T thresholds of 4.5 GeV and 3 GeV for electrons and muons, respectively. Therefore, the soft 2L search targeting such event topologies have low sensitivity in the small mass splitting regime, as presented in Fig. 1.18. To overcome these difficulties with identifying low- p_T leptons, new low- p_T lepton identification methods, dedicated to this search, have been developed. In particular, the new low- p_T electron tagger identifies electron tracks with $p_T = 0.5$ –5 GeV, and the new low- p_T muon tagger identifies muon tracks with $p_T = 1$ –5 GeV.

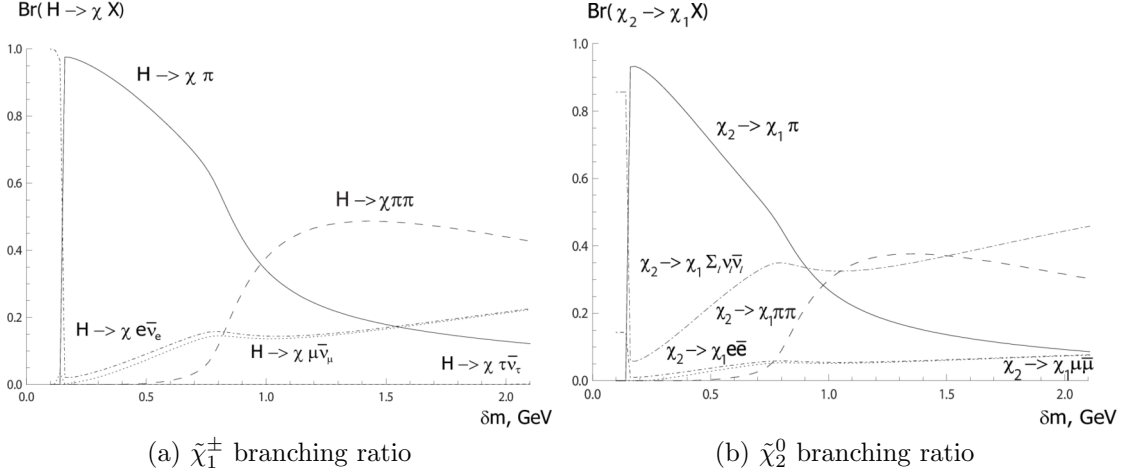


Figure 1.23: Branching ratios of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, as functions of mass splittings [110]. Here, the mass splittings are assumed to be $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, but this has little effect on the branching ratios for leptonic decays.

Fig. 6.1 shows diagrams of the higgsino pair production processes targeted in the search. The targeted event topologies are similar to those targeted in the previous soft 2L search [109]. The lightest neutralino $\tilde{\chi}_1^0$ is stable DM candidate in the considered scenario, thus the two $\tilde{\chi}_1^0$ in the final state are expected to pass through the detectors such that their presence is highlighted only by the observation of a non-negligible missing transverse momentum (E_T^{miss}). In the small mass splitting region, other decay products typically have very small activities, and the only object which could be used to trigger these events is the E_T^{miss} object. However, when the two $\tilde{\chi}_1^0$ are emitted back-to-back in the plane perpendicular to the beampipe, E_T^{miss} will be small, and the events will fail the E_T^{miss} trigger requirement. Therefore, a highly energetic initial state radiation hadronic jet is required to boost the SUSY system and to align the two $\tilde{\chi}_1^0$ to produce large E_T^{miss} .

To improve sensitivity to regions with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2$ –3 GeV, where the soft 2L search could not probe, the analysis targets events where only one lepton (electron or muon) from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ is identified using the standard identification method in ATLAS. The other lepton is assumed to elude the standard identification method, due to its softness. Therefore, only one standard lepton is required, and the other lepton is only required to be reconstructed as a track, which is later required to be identified as a low- p_T lepton track by the newly developed taggers.

Event selection is performed using a state-of-the-art neural network method called parametrized neural network (pNN) [111]. The pNN is optimized to separate signal higgsino production processes and dominant background processes exploiting the features

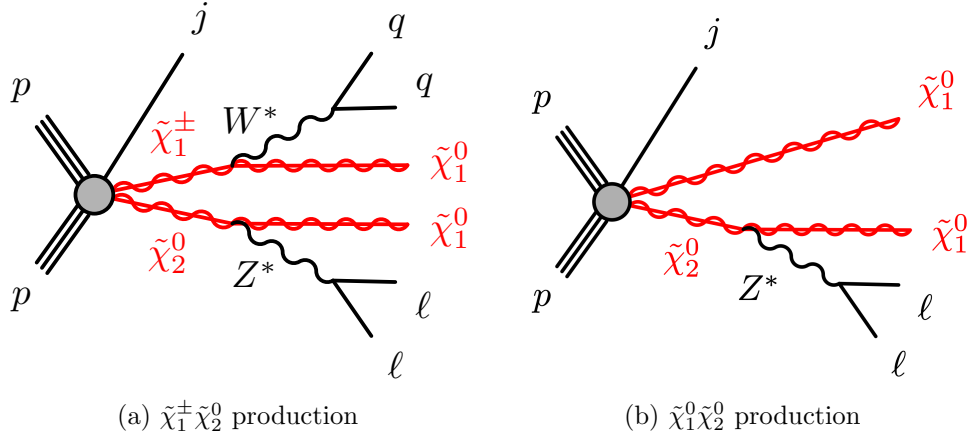


Figure 1.24: Diagrams of the target higgsino pair production processes. The j represents an initial state radiation jet. For $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, leptonic decays of off-shell W boson are also allowed.

of the event topology. As these features depend on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, the pNN is parametrized by $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ to be efficiently trained to identify signal events for various mass splitting scenarios. The analysis is structured to combine the pNN event selection method and the newly developed low- p_T lepton taggers to achieve significant signal to background ratio for higgsinos with small mass splittings. The Signal Region is defined to have high pNN score (corresponding to higgsino event-like topology) and a track with high low- p_T lepton tagger score (corresponding to lepton-like track).

The SM background in the defined Signal Region is estimated using a semi-data-driven method. Dominant contributions are expected to be from W +jets processes, which have a similar event topology; W boson production with leptonic decays ($W \rightarrow \ell \nu$) present a single lepton and a large E_T^{miss} signature. The track identified by the newly developed low- p_T lepton tagger is likely a misidentified hadronic track originating from underlying events. Since there are ambiguities in the modeling of such tracks in the Monte-Carlo (MC) simulations, these “fake lepton track” contributions are inclusively estimated by a data-driven method, later described in Section 7. On the other hand, “true lepton track” contributions, which mainly come from diboson and Z +jets processes are expected to be well-modeled and are estimated directly using MC simulations.

2. Experimental Setup

The search presented in this dissertation exploits 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$, collected by the ATLAS experiment in 2015–2018 during LHC Run 2. This section gives an overview of the LHC and the ATLAS detector.

2.1 Large Hadron Collider

The Large Hadron Collider (LHC) [112] is the world’s largest and the highest-energy circular collider, constructed on the borders of France and Switzerland. It has a circumference of 26.659 km and is designed to collide protons at the center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$. The beampipe is situated in a tunnel about 100 meters underground, and the proton collisions occur at four interaction points (IP), where ATLAS [1], ALICE [113], CMS [114], and LHCb [115] experiments are situated. ATLAS and CMS are large general-purpose experiments which conduct wide varieties of physics programs. ALICE and LHCb are more specialized towards studies of heavy-ion collisions and b-hadrons, respectively.

Table 2.1 summarizes the operation conditions of past and ongoing LHC Runs. The operation of LHC started in 2010 as “Run 1”, in which data was collected until early 2013 at $\sqrt{s} = 7\text{--}8 \text{ TeV}$. In the Long Shutdown 1 (LS1) period, maintenances and upgrades of the accelerator and each detector were carried out. Operation was resumed at $\sqrt{s} = 13 \text{ TeV}$ in 2015 as “Run 2”, which continued until the end of 2018. After another round of maintenances and upgrades in Long Shutdown 2 (LS2), the ongoing operation started in 2022 as “Run 3”, in which the center-of-mass energy is now at $\sqrt{s} = 13.6 \text{ TeV}$.

Table 2.1: Operation conditions for each LHC Run. Only proton operations are considered. $\langle\mu\rangle$ represents the average number of proton-proton interactions per bunch crossing. The figures for delivered integrated luminosity include previous runs. Note that the year and delivered integrated luminosity for Run 3 are expected values.

Operation conditions	Run 1	Run 2	Run 3
Year	2010–2013	2015–2018	2022–2025
Center-of-mass energy [TeV]	7–8	13	13.6
Peak $\langle\mu\rangle$	25	50–60	50–60
Peak instantaneous luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	8×10^{33}	2×10^{34}	2×10^{34}
Delivered integrated luminosity [fb^{-1}]	29	190	450

Fig. 2.1 shows a schematic of diagram of the accelerator complex at CERN. Proton acceleration for the LHC occurs in multiple steps. From 2020, Linear Accelerator 4

(LINAC4) has been used for the seeding of protons; it accelerates negative hydrogen ions to 160 MeV using radiofrequency (RF) cavities. The accelerated ions are then stripped of their electrons during injection from LINAC4 to the Proton Synchrotron Booster, which accelerates the protons to 2 GeV. After the protons are accelerated to 26 GeV by the Proton Synchrotron (PS), they are injected to the Super Proton Synchrotron (SPS) and accelerated up to 450 GeV. Finally, the protons accelerated by the SPS are injected to the LHC.

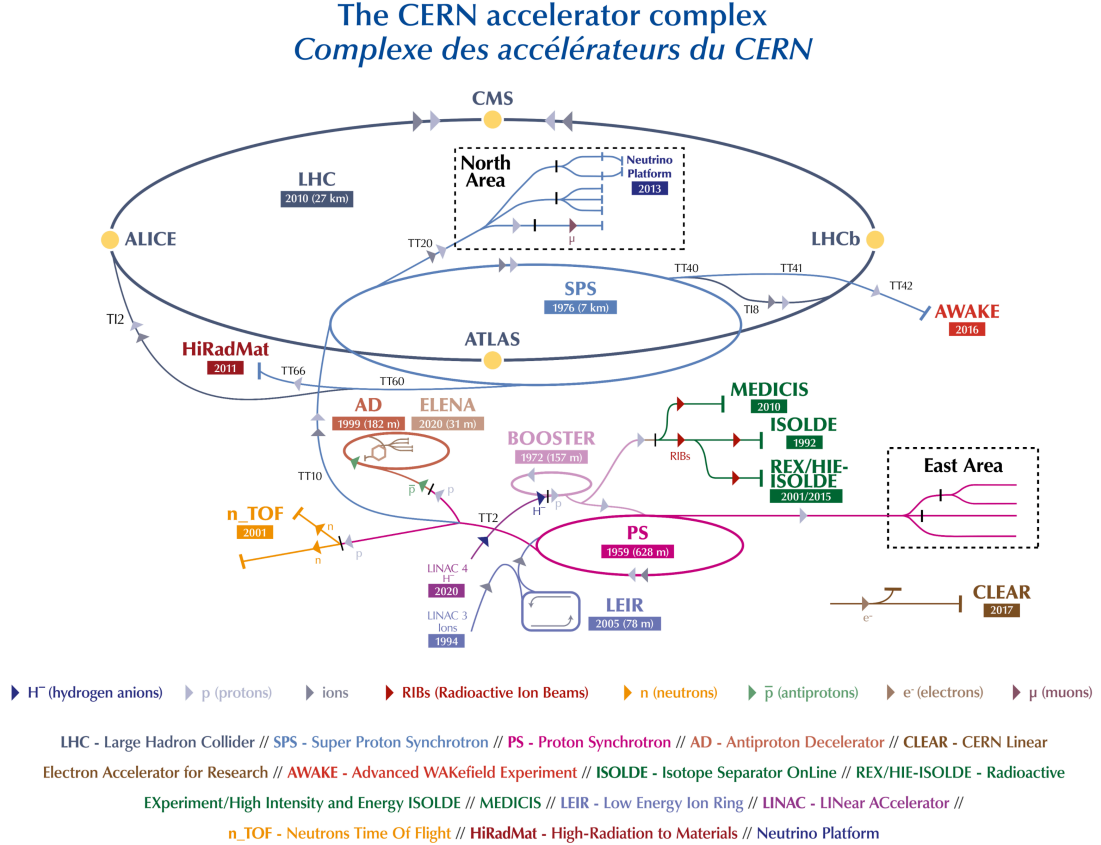


Figure 2.1: A schematic diagram of the CERN accelerator complex [116].

Proton beams at the LHC consist of groups of protons called “bunches” and are accelerated by RF cavities at 400.8 MHz. Since proton bunches are accelerated up to near the speed of light c , in principle, there could be as much as

$$\frac{400.8 \text{ MHz}}{c/26.659 \text{ km}} \approx 35640$$

bunches in one round of the LHC circumference. However, considering margins for beam injection and dumping, the LHC is designed to be injected with a maximum of 2808 bunches, having minimum time spacing of 25 ns. Hence, the frequency of proton bunch crossings at the LHC is $(25 \text{ ns})^{-1} \approx 40.08 \text{ MHz}$. Number of protons per bunch has reached about 1.6×10^{11} in 2023, and the mean number of interactions per bunch crossing is typically larger in Run 3 compared to Run 2 as shown in Fig. 2.2.

The trajectories of proton beams at the LHC are primarily bent by 1232 dipole magnets using superconducting Nb-Ti wires. The dipole magnets are cooled down to 1.9 K

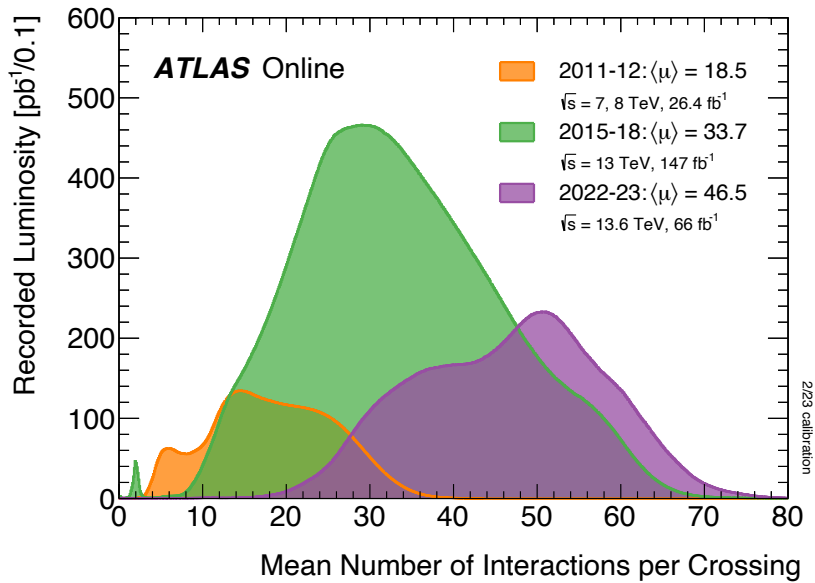


Figure 2.2: Mean number of interactions per bunch crossing for LHC Runs 1, 2, and 3 for all physics data recorded by ATLAS [117].

with superfluid helium and can provide up to magnetic field of about 8.3 T. Moreover, quadrupole magnets with FODO structures are used to keep the beam with finite emittance within its aperture.

2.2 ATLAS detector

The ATLAS detector is a large general-purpose detector situated at Point 1 of the LHC. Fig. 2.3 shows the overall view of the detector. The ATLAS detector can be roughly categorized into three detector groups: Inner Detector, the calorimeters, and the muon spectrometers. The Inner Detector is in the most inner part of the detector and measures p_T of charged particle tracks. The calorimeters surrounding the Inner Detector are responsible for identifying electrons, photons, and hadrons, and measuring their energy. The muon spectrometers consist the outer layers of the detector and measure the p_T of muons. This section gives a brief summary of the magnets, detectors, and Trigger and Data Acquisition system of ATLAS.

2.2.1 Coordinate system

ATLAS experiment adopts a right-handed Cartesian coordinate system shown in Fig. 2.4. In the Cartesian coordinates, the x -axis points towards the center of the LHC ring, the y -axis points upward, and the origin is at the center of the detector, where the beam collisions occur. In terms of the cylindrical coordinate system, the radial distance R and azimuth angle ϕ are also used. Moreover, using the polar angle θ , pseudorapidity η is defined as

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

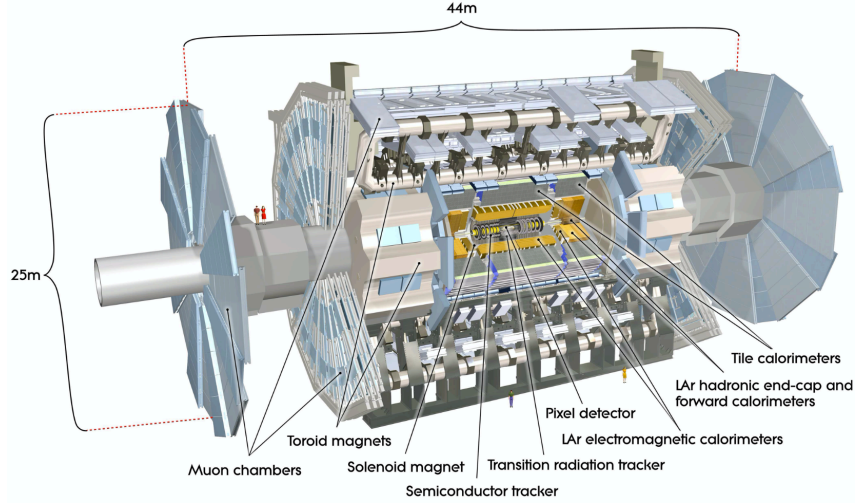


Figure 2.3: Overall view of the ATLAS detector [1]. The cylindrical detector is 44 m long and 25 m in diameter and weighs 7000 t.

which is convenient for describing detector coverage and particle orientation. The region corresponding to the side of the cylinder, is referred to as the “barrel” region, and that corresponding to the base is referred to as the “endcap” region.

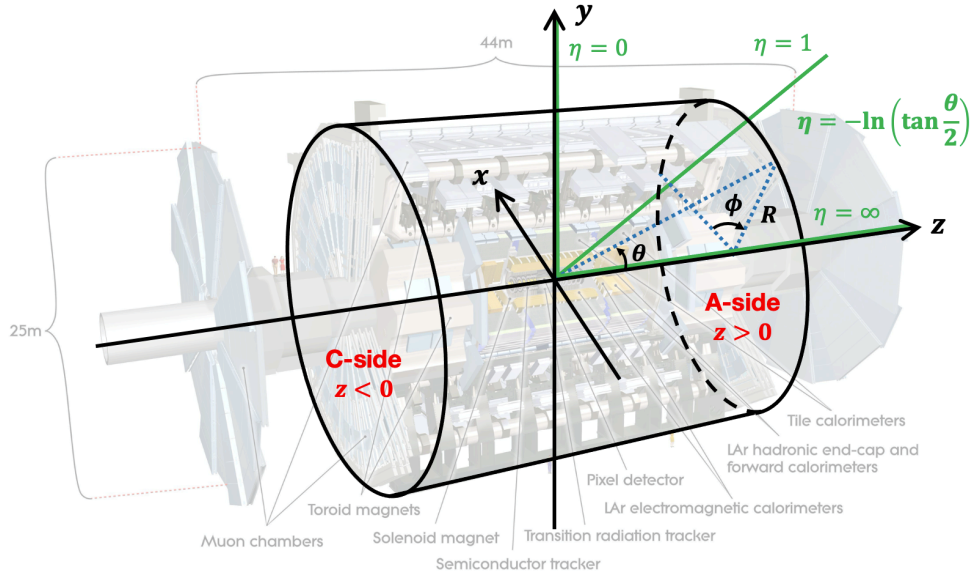


Figure 2.4: Coordinate system of the ATLAS detector. The x -axis points towards the center of the LHC ring, and the y -axis points upward, towards the sky. The side with $z > 0$ is referred to as the A-side, and the side with $z < 0$ is referred to as the C-side. η is often used to describe the coverage of the detectors.

2.2.2 Magnet system

The ATLAS detector has three types of superconducting magnets, which are necessary for particle identification and their p_T measurement. Fig. 2.5 shows a schematic diagram of the ATLAS magnet system. The system consists of three types of magnets: central solenoid, barrel toroid, and endcap toroid.

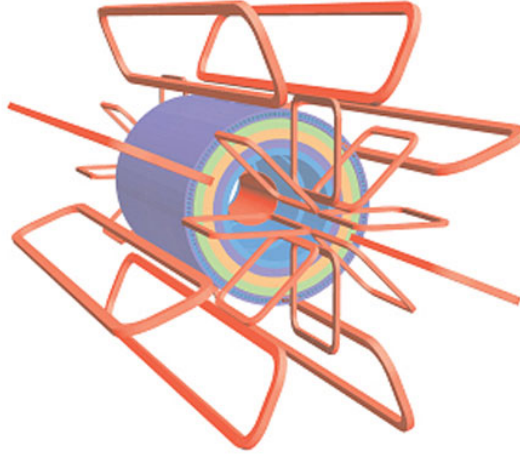


Figure 2.5: Schematic diagram of the ATLAS magnet system [1]. The system consists of three types of magnets: central solenoid, barrel toroid, and endcap toroid.

Central solenoid

The central solenoid magnet is situated between the Inner Detector and the Liquid Argon calorimeter (later described in Sections 2.2.3 and 2.2.4) and is necessary for bending the trajectories of charged particles within the Inner Detector. The magnetic field of the central solenoid is approximately 2 T. Its length is 5.8 m, and its inner and outer diameters are 2.46 m and 2.56 m, respectively.

Barrel toroid

Eight barrel toroid magnets are situated in the barrel regions, in the outer regions with muon systems. These are used to bend trajectories of muons in the barrel regions for p_T measurement. The length of the barrel toroid is 25.3 m, and its inner and outer diameters are 9.4 m and 20.1 m, respectively.

Endcap toroid

Two endcap toroid magnets are situated in the endcap regions, one on each side of the detector. These are used to bend trajectories of muons in the endcap regions for momentum measurement. Each endcap toroid has eight coils, each placed between the barrel toroid coils. Its axial length is 5.0 m, and its inner and outer diameters are 1.65 m and 10.7 m, respectively.

2.2.3 Inner Detector

The ATLAS Inner Detector performs various tracking measurements of charged particles, such as impact parameters, p_T , and charge. As shown in Fig. 2.6, the Inner Detector consists of three subdetectors: Pixel, Semiconductor Tracker (SCT), and Transition Radiation Tracker (TRT).

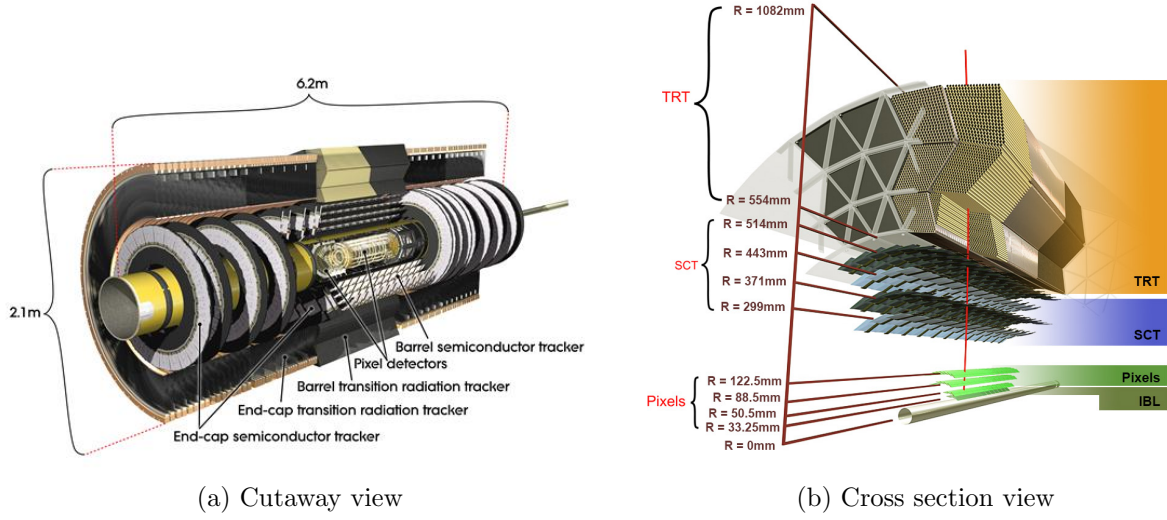


Figure 2.6: Schematic views of the ATLAS Inner Detector [118, 119]. The Inner Detector consists of three subdetectors: Pixel, SCT, and TRT.

Pixel

The Pixel detector is structured from four layers of silicon pixel sensors. The most inner layer at $R = 33.25$ mm is called the Insertable B-Layer (IBL) and was newly introduced in Run 2. The position resolution of the silicon pixels in the IBL is $(\sigma_\phi, \sigma_z) = (8 \mu\text{m}, 40 \mu\text{m})$. The three outer layers used from Run 1 are each called layer-0, layer-1, and layer-2 in the barrel regions and disks in the endcap regions. The position resolution of the silicon pixels in these layers is $(\sigma_\phi, \sigma_{z(R)}) = (10 \mu\text{m}, 115 \mu\text{m})$. Pixel covers regions with $|\eta| < 2.5$.

Semiconductor Tracker

The Semiconductor Tracker (SCT) detector is made of layers of silicon strip sensors. The barrel and endcap regions each consist of four and nine layers, respectively. Each layer has two stereo strips with 40 mrad angle difference to realize 2D stereo measurement. The position measurement of the 2D stereo measurement is $(\sigma_\phi, \sigma_{z(R)}) = (17 \mu\text{m}, 580 \mu\text{m})$. SCT covers regions with $|\eta| < 2.5$.

Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is made of straw-shaped drift tubes with a diameter of 4 mm. The barrel tubes are placed in parallel with the LHC beampipe, whereas the endcap tubes are oriented in the R -direction. TRT tubes are placed in a way that all particles in $|\eta| < 2.0$ (excluding the barrel-endcap gap in $0.8 < |\eta| < 1.0$) pass through at least 36 tubes; by combination with hits provided by Pixel and SCT at small radii, it is possible to reconstruct particle tracks with high precision. The position resolution of TRT itself is $130 \mu\text{m}$ per straw. Although Pixel and SCT have detector coverage of $|\eta| < 2.5$, TRT only covers regions with $|\eta| < 2.0$.

TRT also plays a significant role in electron identification. When charged particle tracks pass through the radiator material between the tubes, photons emitted by transition

radiation are absorbed by the xenon gas in the drift tubes. As subsequent ionization proceeds, the transition radiation is detected through the anode wires centered in the drift tubes. Since the probability of transition radiation increases with the relativistic gamma factor, for particles with energy less than 100 GeV, only electrons are capable of inducing transition radiation within the ATLAS detector. Therefore, electron identification in ATLAS is enhanced by checking the presence of transition radiation in the TRT.

2.2.4 Calorimeters

Fig. 2.7 shows a cutaway view of the ATLAS calorimeter detectors. Calorimeters in ATLAS are roughly categorized into two types by their usage: electromagnetic calorimeters and hadronic calorimeters. Moreover, they can also be categorized by their active material: Liquid Argon (LAr) calorimeters and Tile calorimeters.

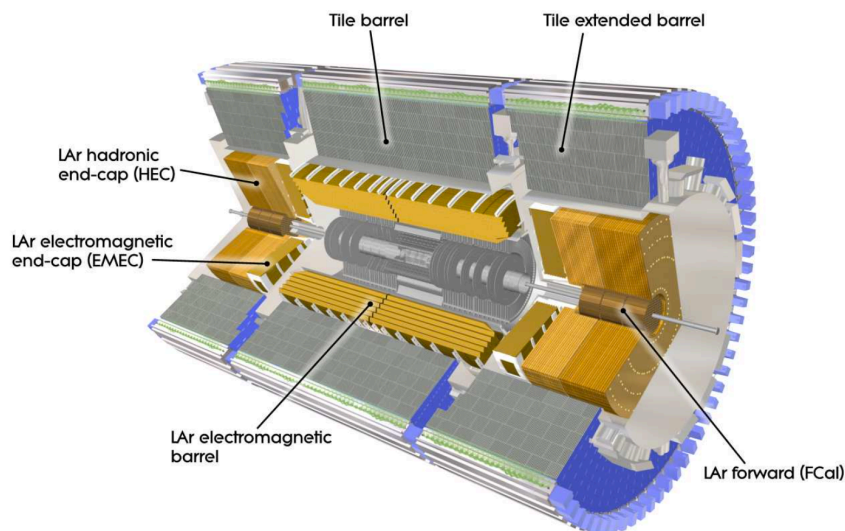


Figure 2.7: Cutaway view of the ATLAS calorimeter detectors [1]. The calorimeters are roughly categorized into two types by their usage: electromagnetic and hadronic.

Electromagnetic calorimeters

The electromagnetic (EM) calorimeters measure the position and energy of electrons and photons. LAr electromagnetic barrel and endcap calorimeters in Fig. 2.7 are the two EM calorimeters. Since LAr calorimeters operate at 88.5 K, these calorimeters are housed in cryostats. EM calorimeters have accordion-like structures made from lead as absorber material and liquid argon as active material as shown in Fig. 2.8. These structures enable full coverage in the ϕ -direction.

The EM barrel calorimeter covers $|\eta| < 1.475$ and has a total thickness of at least $22X_0$, where X_0 is the radiation length, thus assuring sufficient absorption of EM showers. As shown in Fig. 2.8, the EM barrel calorimeter consists of three layers, each having different granularities (cell sizes). Moreover, there is an additional layer called the presampler before the first layer for correcting the electron and photon energy lost by upstream of the calorimeter.

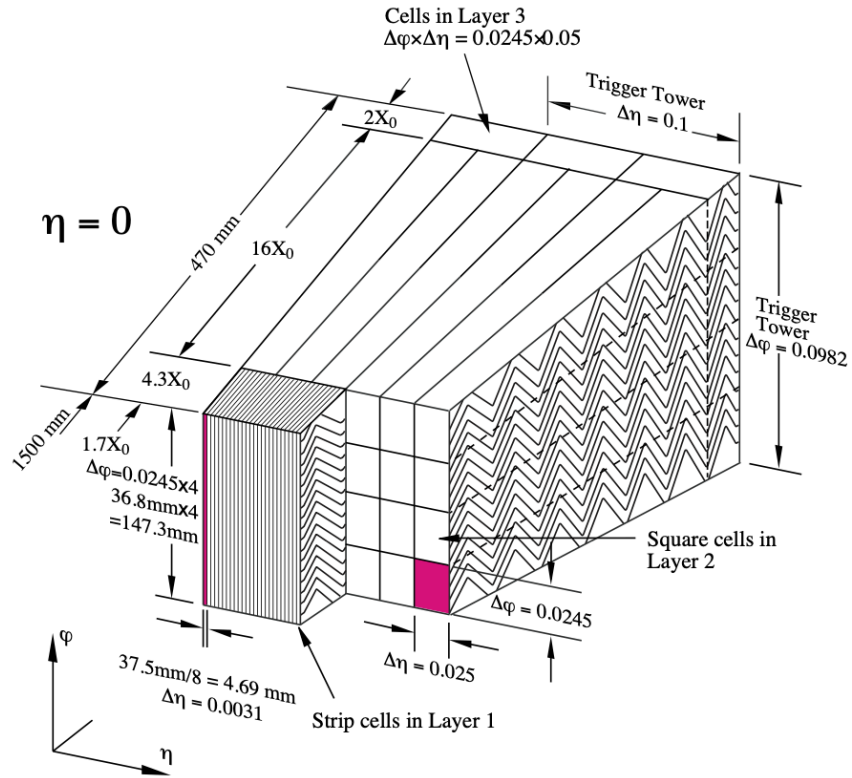


Figure 2.8: Structure of the ATLAS LAr electromagnetic barrel calorimeter [1]. The wavy lines show the accordion-like structure made from lead and liquid argon layers. The LAr electromagnetic endcap calorimeters have similar structures.

The EM endcap calorimeter covers $1.375 < |\eta| < 3.2$ and has a total thickness of at least $24X_0$. Similar to the barrel regions, the EM endcap calorimeters have three layers and an additional presampler layer.

Hadronic calorimeters

Hadronic calorimeters measure the position and energy of hadrons, primarily hadronic jets. Fig. 2.9 shows the cumulative amount of material of each calorimeter in units of hadronic interaction length. The hadronic calorimeters are designed to have sufficient containment of hadronic showers and also to reduce punch-through of hadrons into the muon spectrometers. Hadronic calorimeters are classified into three types: Tile calorimeters, LAr hadronic endcap calorimeters, and LAr forward calorimeters.

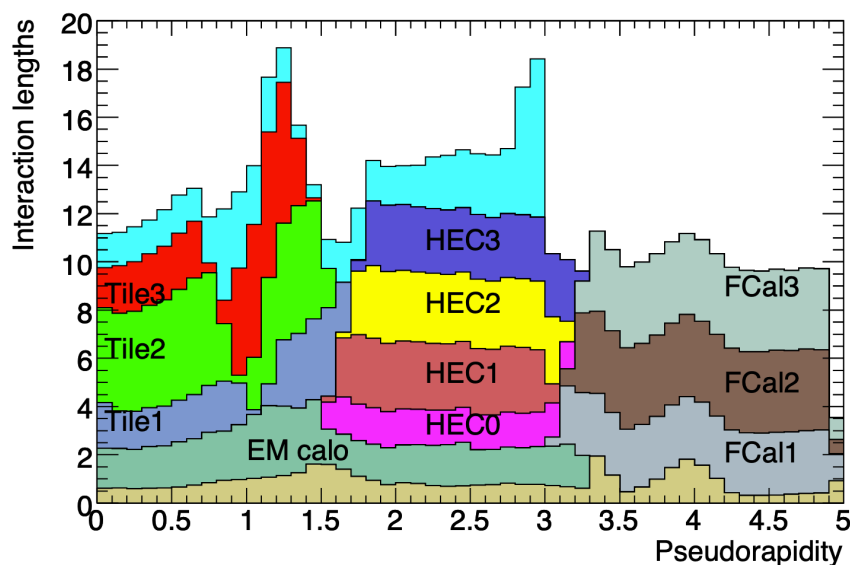


Figure 2.9: Cumulative amount of material in the ATLAS calorimeters in units of hadronic interaction length, as a function of $|\eta|$ [1]. The light blue components show the total amount of material in front of first active layer of the muon spectrometers (up to $|\eta| < 3.0$).

Tile calorimeters are made from steel as absorber material and scintillator tiles as active material. Tile barrel calorimeter covers regions with $|\eta| < 1.0$, and the Tile extended barrel covers regions with $0.8 < |\eta| < 1.7$. The thickness of the Tile calorimeters corresponds to $7.4\lambda_0$, where λ_0 is the hadronic interaction length. Tile barrel and extended barrel are both divided into 64 modules in the ϕ -direction as shown in Fig. 2.10.

LAr hadronic endcap calorimeters are placed in the endcap regions, outside the EM endcap calorimeters, covering $1.5 < |\eta| < 3.2$. Instead of lead, LAr hadronic endcap calorimeters adopt copper as their absorber material. The granularity of LAr hadronic endcap calorimeters is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for $1.5 < |\eta| < 2.5$ and $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ for $2.5 < |\eta| < 3.2$.

LAr forward calorimeters cover the forward regions of ATLAS, in particular, regions with $3.1 < |\eta| < 4.9$. The forward calorimeter, consisting of three layers, is used as both EM and hadronic calorimeters; the first layer is used as an EM calorimeter, and the second and third layers are used as hadronic calorimeters. As for the absorber material, the first layer adopts copper, and the second and third layer adopt tungsten.

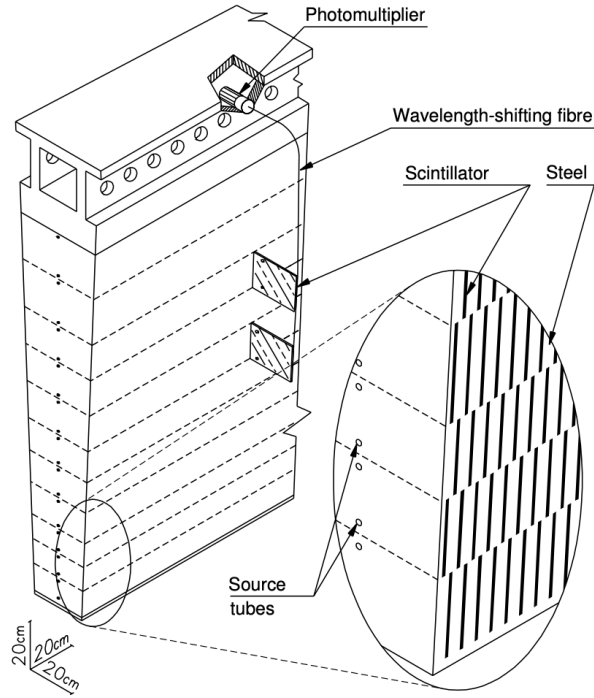


Figure 2.10: Structure of the ATLAS Tile calorimeter module [1]. Tile barrel and extended barrel calorimeters are divided into 64 modules having $\Delta\phi = 5.625^\circ$. As zoomed in on the right, Tile calorimeters have sandwich-like structures made from tile scintillators and steel.

2.2.5 Muon spectrometers

The muon spectrometers consist the most outer layers of the ATLAS detector and have the significant role of reconstruction and identification of muons. Although the muon detectors have been partially upgraded for the ongoing Run 3, the configurations for Run 2 are summarized in this section, as the search presented in this paper uses Run 2 data.

Fig. 2.11 shows the overall view of the ATLAS muon spectrometers, which consist of four subdetectors: Monitored Drift Tube (MDT), Cathode Strip Chamber (CSC), Resistive Plate Chamber (RPC), and Thin Gap Chamber (TGC). MDT and CSC have high position resolution and are responsible for precision p_T measurements of muons. RPC and TGC have high timing resolution and provide muon trigger signals.

Monitored Drift Tube

Monitored Drift Tube (MDT) is a precision measurement muon detector and consists of three layers of drift chambers for both barrel and endcap regions. The coverage is $|\eta| < 2.0$ for the most inner layer and $|\eta| < 2.7$ for the outer two layers.

Fig. 2.12a shows the structure of the MDT drift tube. Each drift tube is made of aluminum and is about 30 mm in diameter. When a muon passes through the tube, the Ar/CO_2 gas is ionized, and the resulting electrons drift towards the anode wire, with a maximum drifting time of 700 ns. The position resolution of each tube is estimated to be $80 \mu\text{m}$. Fig. 2.12b shows the MDT chamber structure. Each chamber has one or more “multilayers”, which consist of 3–4 layers of drift tubes. Although the chamber frames have robust structures made of aluminum, a laser-based alignment system is implemented

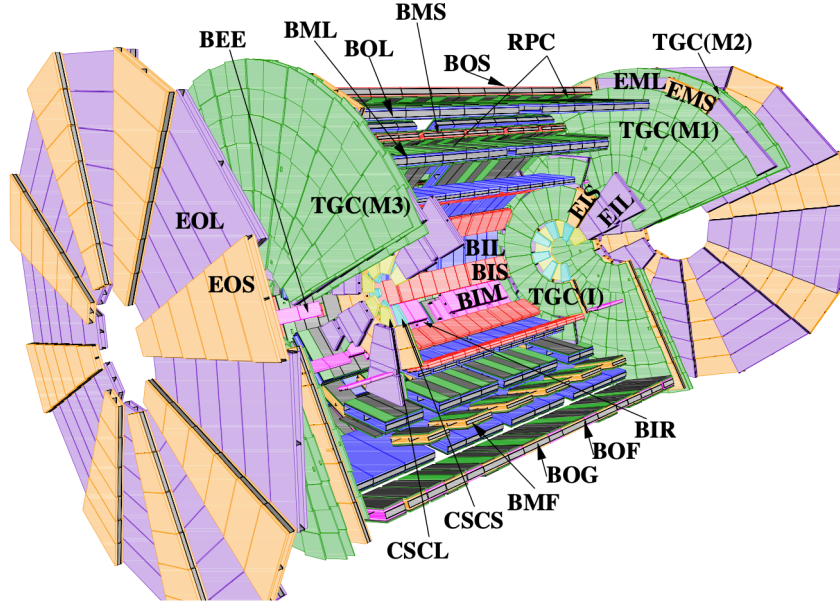


Figure 2.11: Overall view of the ATLAS muon spectrometers [1]. Four detectors consist the muon system: MDT, CSC, RPC, and TGC.

to detect distortions from aging.

Cathod Strip Chamber

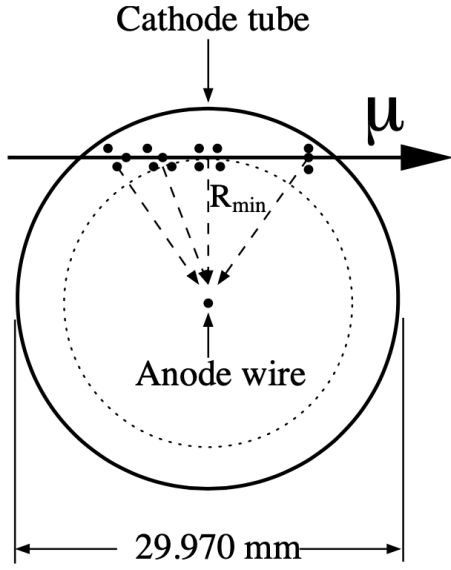
Cathode Strip Chamber (CSC) is a multiwire proportional chamber specifically made for performing muon precision measurements in the endcap regions with $2.0 < |\eta| < 2.7$. Although the MDT chambers also cover the same regions, muon hit frequency in the endcap regions exceeds the stable operation threshold of MDT chambers of 150 Hz/cm^2 . Hence, the CSC was prepared complementarily for precision measurement of muons in the endcap regions.

Fig. 2.13a shows the layout of CSC chambers. There are 16 chambers for each CSC wheel: eight large and eight small chambers. In each chamber, anode wires are placed in the radial direction with spacings of 2.5 mm, and cathode strips are placed perpendicularly in the ϕ -direction, as shown in Fig. 2.13b. When a muon passes through the chamber, the Ar/CO_2 gas is ionized, resulting in an electron avalanche. The position of the muon is determined by reading out the charge distribution on the cathode strips. The position resolution is $60 \mu\text{m}$ per CSC plane, and the timing resolution is 7 ns, sufficiently high to withstand high muon hit frequency in the endcap regions.

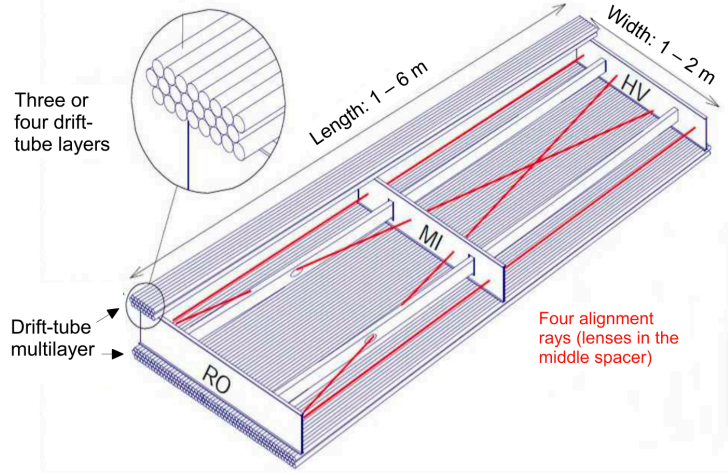
The CSC was decommissioned after Run 2 and has been upgraded to the New Small Wheel (NSW) detector in the ongoing Run 3.

Resistive Plate Chamber

Resistive Plate Chamber (RPC) is a gaseous parallel electrode-plate detector, designed to provide muon trigger signals in $|\eta| < 1.05$. RPC consists of three stations, each of which has a structure shown in Fig. 2.14. Each station has two units, each having two gas layers for measuring (η, ϕ) of the muon hit position.

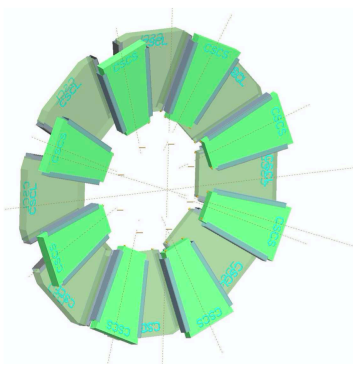


(a) Drift tube structure

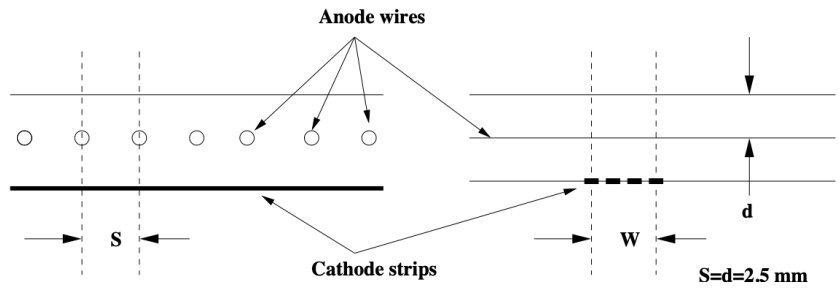


(b) Chamber structure

Figure 2.12: Schematic diagram of the MDT drift tube and chamber structures [1]. Each chamber is made from one or more multilayers, where each multilayer has 3-4 layers of tubes. The red lines on Fig. 2.12b show the lasers used for the alignment system.



(a) Layout of CSC chambers



(b) CSC anode wires and cathode strips

Figure 2.13: Schematic diagram of the CSC chambers and the structure of anode wires and cathode strips [1].

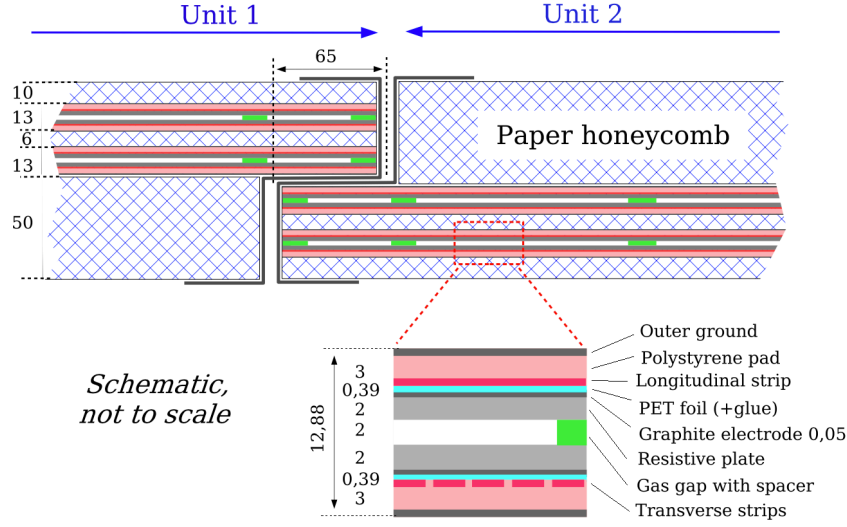


Figure 2.14: Cross-section view of the RPC station [1]. The unit of length is in mm. Each station has two units, each having two gas layers that measure (η, ϕ) of the muon hit position.

The chambers of RPC consist of a 2 mm thick gas layer sandwiched by two highly resistive plastic plates. An electron avalanche is induced when a muon passes through the nonflammable gas mixture (94.7% $\text{C}_2\text{H}_2\text{F}_4$, 5.0% Iso- C_4H_{10} , 0.3% SF_6), with applied voltage of 4.9 kV/mm. The position resolution of RPC is 10 mm in both z - and ϕ -directions, and the timing resolution is 1.5 ns, sufficiently high to operate as a trigger detector.

Thin Gap Chamber

Thin Gap Chamber (TGC) is a multiwire proportional chamber detector, which provides muon trigger signals in the endcap regions with $1.05 < |\eta| < 2.4$. TGC is roughly categorized into two types: TGC Big Wheel (TGC-BW) and TGC Inner (TGC-I) situated farther from and closer to the IP relative to the endcap toroid magnet, respectively.

Fig. 2.15a shows the gas chamber structure of TGC. The anode wires have spacings of 1.8 mm, and the cathode strips are placed 1.4 mm apart from the wires, resulting in a 2.8 mm thick gas layer. When a muon passes through the gas mixture (55% CO_2 , 45% $n\text{-C}_5\text{H}_{12}$), an electron avalanche is induced by an applied voltage of 2.8 kV. The wires detect the positive ions caused by the avalanche, and the cathode strips detect the image charges of those ions. The position resolution of each chamber is 2–6 mm in the R -direction and 3–7 mm in the ϕ -direction, and its timing resolution is about 4 ns.

TGC-BW and TGC-I both consist of multiple stations, each having two or three gas layers, as shown in Fig. 2.15b. The station with three and two gas layers are called triplets and doublets, respectively. TGC-BW have three stations, one triplet and two doublets, which are inclusively used to measure the p_T of muons. TGC-I have two doublet stations called Endcap Inner (EI) and Forward Inner (FI), each covering different η regions. The Inner stations are primarily used to veto muon candidates which do not come from the IP. However, similar to the CSC, TGC-FI has been decommissioned after Run 2 and has been replaced by the NSW detector.

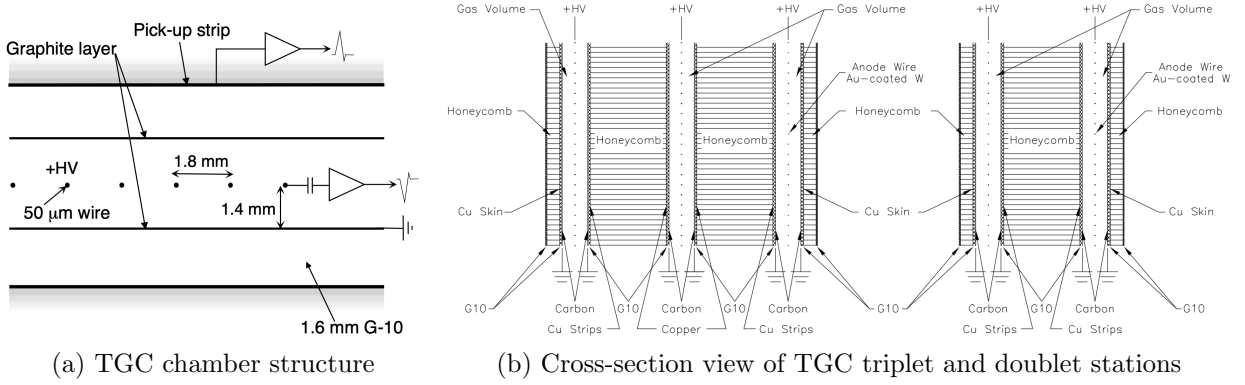


Figure 2.15: Schematic diagram of the TGC chambers and stations [1].

2.2.6 Luminosity detectors

Precise measurement of integrated luminosity is necessary for properly normalizing the simulated dataset for comparison with collected data. The integrated luminosity of the data used in the search presented in this paper has been measured by the luminosity detectors of ATLAS.

Instantaneous luminosity $\mathcal{L}$ is calculated with

$$\mathcal{L} = \frac{\mu n_b f}{\sigma}, \quad (2.2)$$

where n_b is the number of colliding bunches, $f = 11.246$ kHz is the frequency of LHC proton bunch revolution, σ is the cross section of inelastic proton-proton collisions, and μ is the number of proton-proton interactions per bunch crossing, averaged over all colliding bunches [120]. Although $\sigma = 80$ mb is assumed in all experiments at the LHC, the instantaneous luminosity is measured independent of that assumption; $\mathcal{L}$ is calculated by measuring the visible interaction rate per bunch μ_{vis} and the visible cross section σ_{vis} using the following luminosity detectors.

LUCID

LUCID is a luminosity detector situated in the forward regions of the ATLAS detector, at $z = \pm 17$ m from the IP. LUCID consists of 16 photonmultiplier tubes surrounding the beampipe, which detect Cherenkov light emitted by charged particles passing through the C_4F_{10} gas filled in the tubes. μ_{vis} is then measured online by counting the number of Cherenkov light signals, each corresponding to one or more inelastic proton-proton collisions. On the other hand, σ_{vis} is measured during special LHC fills with the van der Meer (vdM) scan method. LUCID was upgraded to LUCID-2 [121] at the start of Run 2 to cope with increased energy and higher luminosity conditions.

Beam Conditions Monitor

Beam Conditions Monitor (BCM) detector is at $z = \pm 1.84$ m from the IP and consists of four diamond sensors. BCM mainly provides beam conditions information and beam

abort functionalities for protecting the ATLAS inner detector. It was the main luminosity detector in Run 1, however, its use was limited to consistency checks for special configuration runs in Run 2, due to technical problems such as radiation damage.

2.2.7 Trigger and Data Acquisition system

As mentioned in Section 2.1, proton bunch crossings at the LHC occur at 40 MHz, and 50–60 proton interactions occur in each bunch crossing. However, target processes of interest such as physics beyond the SM and Higgs production, have cross sections much smaller compared to those of proton-proton inelastic scattering. Therefore, a sophisticated Trigger and Data Acquisition (TDAQ) system is necessary to select and record data with physics of interest, making efficient use of limited readout bandwidths and offline computing resources. Fig. 2.16 shows the overview of the ATLAS TDAQ system in LHC Run 2. ATLAS adopts a two-step trigger system consisting of the hardware-based Level-1 Trigger and the software-based High Level Trigger.

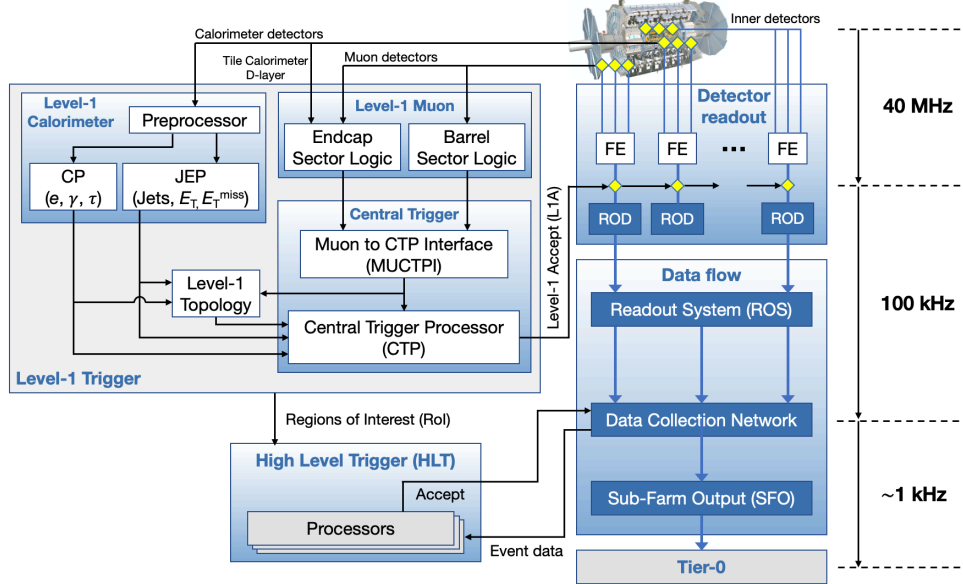


Figure 2.16: Overview of the ATLAS TDAQ system in LHC Run 2 [122]. On the left is the trigger system, and on the right is the DAQ system.

Level-1 Trigger

The Level-1 Trigger is a hardware-based trigger system, which reduces the data rate from 40 MHz to about 100 kHz using calorimeter and muon information. In the Level-1 calorimeter (L1Calo) trigger, analog signals from the calorimeters are first digitized and calibrated by the preprocessor and then sent to the Cluster Processor (CP) and Jet/Energy-sum Processor (JEP). The CP system identifies electron, photon, and tau candidates, whereas the JEP system identifies hadronic jet candidates and calculates the total jet energy sum and missing transverse energy. In the Level-1 muon (L1Muon) trigger, muon candidates are identified in the barrel and endcap regions using muon hit information from RPC and TGC detectors, respectively. Based on the information from

L1Calo and L1Muon triggers, Central Trigger Processor (CTP) forms the final L1 trigger decision. Data corresponding to the L1 trigger decision is then read out from the detector frontend systems to the ATLAS readout system. The Level-1 Trigger is required to operate with a fixed latency within $2.5 \mu\text{s}$.

High Level Trigger

The High Level Trigger (HLT) is a software-based trigger system, which further reduces the data rate to 1–2 kHz using more precise and CPU-intensive algorithms, motivated by physics of interest. For event data read out to the ATLAS readout system, the HLT performs online reconstruction based on Region-of-Interest (RoI) information passed on from the Level-1 Trigger. The HLT decision is processed within a few hundred milliseconds.

Data Acquisition

In all detector subsystems, data for every bunch crossing is temporarily stored in the detector frontends. Subsequently, only the corresponding data accepted by the Level-1 Trigger is further read out to the Readout Drivers (RODs), in which event data is organized into a common format. The formatted data is then passed to the ATLAS central Readout System (ROS), which is responsible for buffering event data from all detector subsystems and transferring them to the HLT system. Event data accepted by the HLT is sent to permanent storage via the Sub-Farm Output (SFO).

3. Data and Simulated Event Samples

This section describes the details of the data and simulated event samples used for the search presented in this dissertation.

3.1 Dataset

The search presented in this dissertation uses the full LHC Run 2 dataset collected by the ATLAS detector in 2015–2018, corresponding to 140 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. Table 3.1 shows the integrated luminosity of the data used in the analysis for each year. The relative uncertainty of the total integrated luminosity is 0.83% [120], obtained using the LUCID-2 detector [121] for the primary luminosity measurements, complemented by measurements using the Inner Detector and calorimeters.

Table 3.1: Integrated luminosity of p-p data used in the analysis for each year [120].

Year	Integrated luminosity [fb^{-1}]
2015	3.24 ± 0.04
2016	33.40 ± 0.30
2017	44.63 ± 0.50
2018	58.79 ± 0.64
Total	140.07 ± 1.17

3.2 Trigger

As mentioned in Section 1.3.3, the search targets signal event topologies with high missing transverse momentum ($E_{\text{T}}^{\text{miss}}$), resulting from the two $\tilde{\chi}_1^0$ in the final state. Since the decay products from $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are too soft to be triggered on, $E_{\text{T}}^{\text{miss}}$ triggers are used for all data used in the search. In particular, the lowest unpresecaled $E_{\text{T}}^{\text{miss}}$ triggers shown in Table 3.2 are used for each data-taking period. Although increasing pileup levels had a large impact on triggers during Run 2, only small adjustments were made for the L1 threshold for $E_{\text{T}}^{\text{miss}}$ triggers, because the trigger rate was reduced by adjusting the calorimeter noise thresholds [123].

On the other hand, the HLT algorithm for $E_{\text{T}}^{\text{miss}}$ triggers made a large evolution between 2016 and 2017. In 2015-2016, the `mht` algorithm was used. This adopts a calibrated

Table 3.2: List of E_T^{miss} triggers used for each data-taking period [123]. For 2017–2018, the two HLT thresholds each correspond to the threshold for the **pufit** and **cell** algorithm, respectively.

Year	Period	L1 threshold [GeV]	HLT threshold [GeV]	HLT algorithm
2015	All	50	70	mht
	A–D3	50	90	mht
2016	D4–F1	50	100	mht
	F2–	50	110	mht
2017	All	55	110/50	pufit/cell
2018	B–C5	50	110/70	pufit/cell
	C6–	50	110/65	pufit/cell

jet based E_T^{miss} calculation, which subtracts contributions from pileup. From 2017, the **pufit** algorithm was introduced, which performs pileup corrections. This was combined with the **cell** algorithm, which determines the E_T^{miss} from calorimeter cells, without any corrections on pileup effects.

Fig. 3.1 shows the efficiencies of the E_T^{miss} trigger for each year of Run 2. The efficiencies are measured with $Z \rightarrow \mu\mu$ processes, in which the p_T of the dimuon system could be treated as E_T^{miss} , because muons have little interaction with the calorimeters. The trigger is fully efficient and its fluctuation in efficiency could be ignored for $E_T^{\text{miss}} > 200$ GeV, which is the required E_T^{miss} threshold for all kinematic regions used in the analysis.

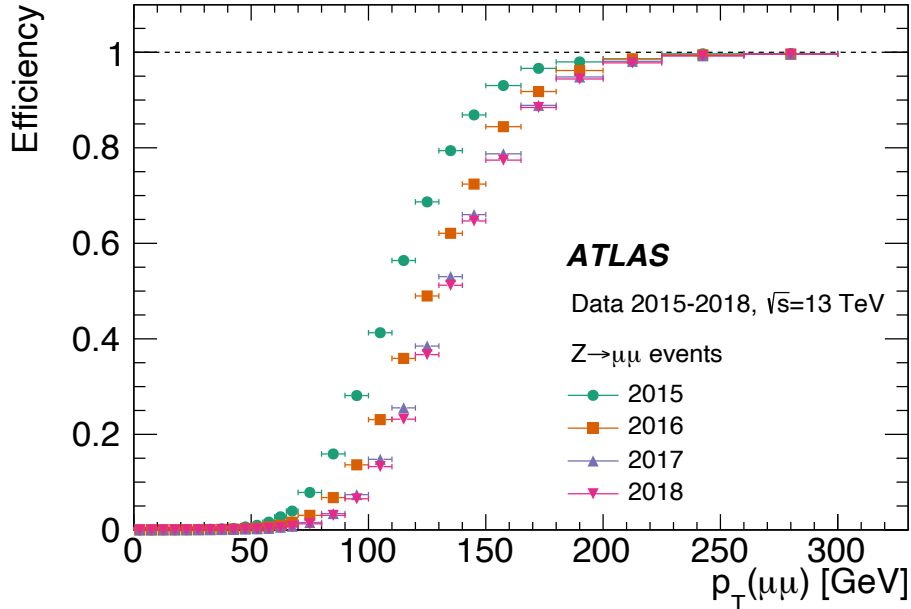


Figure 3.1: Efficiency of the ATLAS E_T^{miss} trigger for each year of Run 2 [123]. The efficiency is measured with $Z \rightarrow \mu\mu$ processes, and the efficiency is shown as a function of $p_T(\mu\mu)$, which corresponds to E_T^{miss} .

3.3 Monte-Carlo sample simulation

This section highlights the simulated event samples for signal higgsino production processes and background processes used in the analysis. The simulation is done using Monte-Carlo (MC) methods; the simulated event samples are hereinafter referred to as MC samples in this dissertation.

3.3.1 Signal MC sample generation

As mentioned in Section 1.3.1, the search presented in this dissertation assumes a simplified higgsino-like LSP model, a typical case where the LSP is dominated by the higgsino component. In such a model, the masses of the higgsino triplet ($\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$) have the following relations:

- $m(\tilde{\chi}_2^0) > m(\tilde{\chi}_1^\pm) > m(\tilde{\chi}_1^0)$,
- $m(\tilde{\chi}_1^\pm) = \frac{1}{2}\{m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)\}$.

Thus, the signal MC samples have been generated with the above assumptions. All other SUSY particles are assumed to be much heavier and not have any phenomenological relations with the higgsinos. Total of 28 mass points have been considered to target the unexplored regions: the considered mass splitting values are $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 1.0, 1.5, 2.0, 3.0, 4.0$, and 5.0 GeV, and the considered masses are $m(\tilde{\chi}_1^0) = 85, 100, 125, 150$, and 175 GeV. Fig. 3.2 shows an overall view of the mass points used for signal MC sample generation, compared to the exclusion limits set by other searches. For each of the mass points, separate MC samples have been generated to properly calculate the cross sections for each of the three production processes: $\tilde{\chi}_2^0 \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^\pm \tilde{\chi}_1^\mp$.

The signal MC samples have been generated at leading order (LO) with MG5_aMC@NLO 2.9.3 [124] using the NNPDF23LO [125] parton distribution function (PDF) set. The spin of the higgsinos were conserved using MADSPIN [126]. The events were then interfaced with PYTHIA 8.245 [127] to model parton showering, hadronization, and underlying events using A14 tune [128]. The matching between the matrix element and parton shower was performed using the CKKW-L scheme [129], with the merging scale set to 15 GeV.

For efficient generation of the targeted event topology, several requirements have been imposed during the generation step. First, due to the ISR topology targeted by this search, the samples are generated only for events associated with at least one hadronic jet with $p_T > 50$ GeV. The effect of this requirement on the production cross section is considered by applying a dedicated correction factor, later described in this section. Moreover, as an event filter, the transverse component of the momentum sum of non-interacting particles (corresponding to E_T^{miss} at reconstruction level) is required to be more than 50 GeV. One lepton (electron or muon) filter with $p_T > 2$ GeV are also applied to ensure high production efficiency of the targeted high E_T^{miss} and one lepton topology. For these two filters, corresponding filter efficiencies are applied to the samples, ranging from 10% to 70%, with high dependence on the mass splitting value.

The production cross sections and their uncertainties are calculated to NLO+NLL accuracy using RESUMMINO [130–135]. Since these cross sections do not account for the ISR jet as mentioned above, they must be corrected by a factor of $\sigma(\geq 1 \text{ jet})/\sigma(\geq 0 \text{ jet})$.

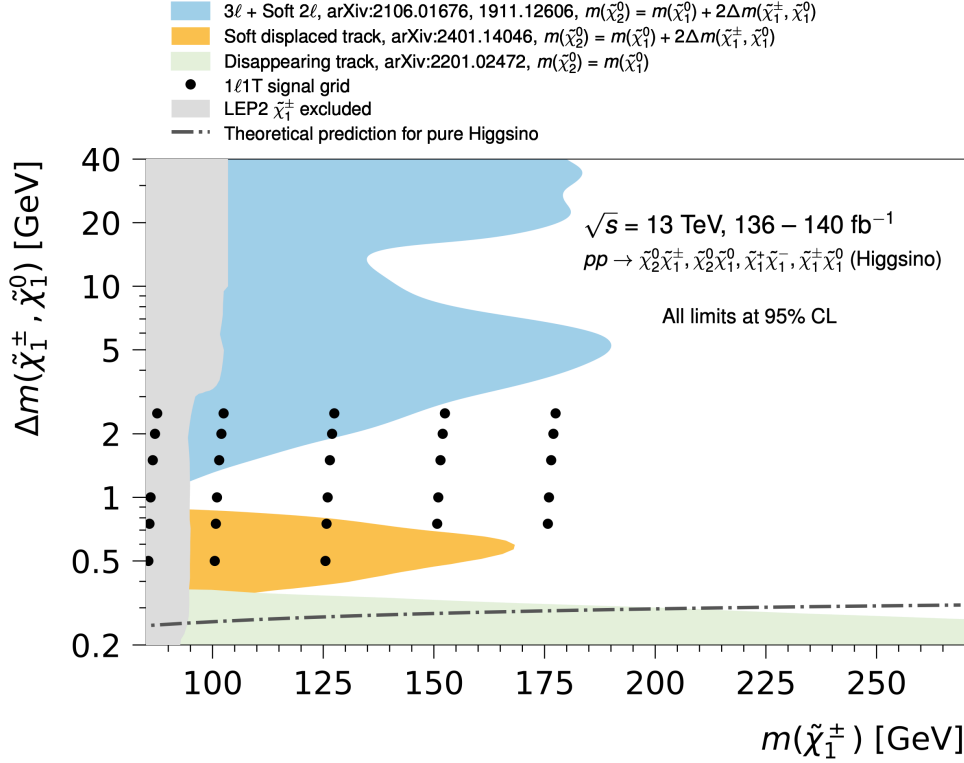


Figure 3.2: Overall view of the signal mass points used in the search in the $m(\tilde{\chi}_1^\pm)$ vs $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ plane. The mass points have been chosen to search for regions with small mass splitting values, not yet explored by other searches.

This correction factor is derived for each signal point by preparing low statistics samples which include the 0-jet process, and their typical values range from 0.2 to 0.3. The corrected channel inclusive cross sections range from about 300 fb for the lowest mass point to about 30 fb for the highest mass point, satisfying the relation $\sigma(\tilde{\chi}_2^0\tilde{\chi}_1^\pm) > \sigma(\tilde{\chi}_2^0\tilde{\chi}_1^0) > \sigma(\tilde{\chi}_2^0\tilde{\chi}_1^-)$.

3.3.2 Background MC sample generation

As later described in Section 7, although the dominant background contribution from “fake” lepton tracks, mainly misidentified hadronic tracks, is estimated using a data-driven method, small contribution of “true” lepton tracks, actual leptons coming from physics processes, is estimated using background MC samples. Table 3.3 shows the list of background MC samples used in the analysis. Note that processes with little “true” contribution, such as $t\bar{t}$, single top, dijet, and γ +jets, have also been included just in case, but were later found to be negligible.

SHERPA [136] and NNPDF30NNLO [125] PDF sets are used for the modeling of W , Z , and γ production associated with hadronic jets, as well as diboson (WZ , ZZ , WW) production processes. W +jets and Z +jets processes are generated with SHERPA 2.2.11, whereas γ +jets processes are generated with SHERPA 2.2.2. Diboson processes are mainly generated with SHERPA 2.2.2 but partially generated with SHERPA 2.2.1.

POWHEG [137–139] interfaced with PYTHIA 8.2 [127] for showering is used for single top production (s-channel, t-channel, and tW), $t\bar{t}$, and dijet processes. For these processes,

Table 3.3: List of background MC samples used in the analysis.

Physics process	Generator	PDF set	Parton shower	Tune
$W(\rightarrow \ell\nu)+\text{jets}$	SHERPA 2.2.11	NNPDF30NNLO	SHERPA	SHERPA
$Z(\rightarrow \ell\ell)+\text{jets}$	SHERPA 2.2.11	NNPDF30NNLO	SHERPA	SHERPA
Diboson ($WZ/ZZ/WW$)	SHERPA 2.2.2/2.2.1	NNPDF30NNLO	SHERPA	SHERPA
$t\bar{t}$	POWHEG-BOX v2	NNPDF23LO	PYTHIA v8.230	A14
Single top (s/t-channel, tW)	POWHEG-BOX v2	NNPDF23LO	PYTHIA v8.230	A14
Dijet	POWHEG-BOX v2	NNPDF23LO	PYTHIA v8.235/v8.243	A14
$\gamma+\text{jets}$	SHERPA 2.2.2	NNPDF30NNLO	SHERPA	SHERPA

NNPDF23LO is used for the PDF sets.

3.3.3 Detector and pileup simulation

All signal and background MC samples are processed through the full ATLAS simulation framework [140], which uses GEANT4 [141]. Simulation of the effects of pileup is performed by generating soft QCD processes separately and overlaying them to each of the hard-scatter events. The MC samples are then reweighted to have a matching pileup distribution with observed data, with respect to the number of pileup through the data-taking periods.

4. Standard Object Reconstruction and Identification

For both recorded data and simulated MC samples, detector-level information is processed and translated into physics-level “objects” through reconstruction and identification. This section summarizes the reconstruction and identification of standard objects used in this search.

4.1 Track

The trajectories of charged particles are reconstructed as tracks using the hit information in the Inner Detectors. The tracks used in this search are standard tracks reconstructed by the primary “inside out” algorithm [142]. For each layer of Pixel and SCT detectors, the algorithm first combines signals into clusters, which are further converted to three dimensional “space points”. Next, track seeds are formed from three space points, expected to be originating from the same charged track trajectory. Track seeds are then extended through a combinatorial Kalman filter [143], which yield a set of potential track candidates. Since these candidates still have overlaps, an ambiguity resolution algorithm and a subsequent global χ^2 fit method are applied to obtain the final tracks.

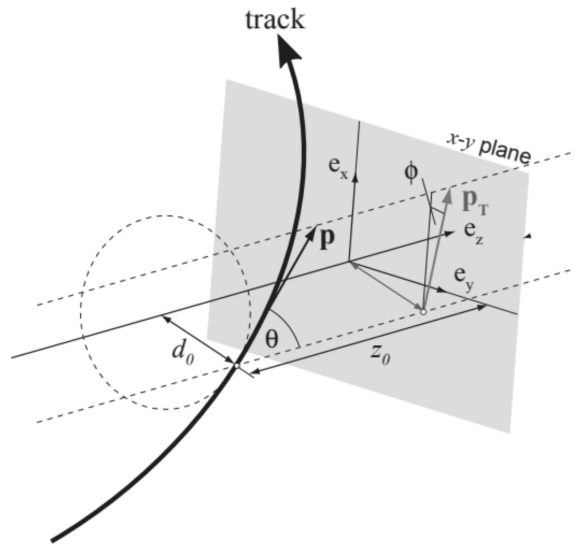
After the final track candidates are obtained from the Pixel and SCT hits, extensions to the TRT detector is attempted. TRT extension is performed in a similar way using a Kalman filter and a global χ^2 fit. At least nine TRT hits are required to perform the extension, and the extension may be rejected when the fit quality is detrimentally affected.

Tracks are described by five parameters using a perigee representation as shown in Fig. 4.1. d_0 and z_0 are the transverse and longitudinal impact parameters with respect to the primary vertex, described later in Section 4.2. ϕ and θ are the azimuth and polar angles similar to those defined in Section 2.2.1. q/p is the charge of the track divided by the magnitude of its momentum, measured from the curvature of the track under the solenoid magnetic field.

Preselection requirements in this search

The following preselection requirements, defined as the *TightPrimary* working point, are imposed to the tracks used in the analysis.

- $p_T > 500$ MeV
- $|\eta| < 2.5$



Global track parameters e.g.
wrt. perigee

$$\left(d_0, z_0, \phi, \theta, \frac{q}{p} \right)$$

Figure 4.1: Schematic diagram of a track in the ATLAS detector and its parameters.

- $N_{\text{Si}} \geq 7$: At least 7 hits in the silicon detectors (Pixel and SCT, including dead sensors)
- $N_{\text{mod}}^{\text{sh}} \leq 1$: Less than or equal to 1 Pixel/SCT hits assigned to multiple tracks
- $N_{\text{Si}}^{\text{hole}} \leq 2$: Less than or equal to 2 Pixel/SCT hits missing
- $N_{\text{Si}} \geq 9$ (if $|\eta| < 1.65$): At least 9 hits in the silicon detectors (if $|\eta| < 1.65$)
- $N_{\text{Si}} \geq 11$ (if $|\eta| > 1.65$): At least 11 hits in the silicon detectors (if $|\eta| > 1.65$)
- $N_{\text{IBL}} + N_{\text{B-Layer}} > 0$: At least 1 hit in the two innermost layers (IBL or B-Layer) if expected
- $N_{\text{pix}}^{\text{hole}} = 0$: No Pixel hits missing

Further track selection criteria used in the analysis are discussed later in Section 6.

4.2 Vertex

The positions where the proton-proton collisions occurred, often referred to as the primary vertices, must be reconstructed for each event to find the “hard-scatter” vertex and provide a reference point for object reconstruction. Primary vertex reconstruction is performed using vertex finding and fitting algorithms, exploiting reconstructed track information [144].

A vertex seed is first found from the maximum in the z coordinate distribution of the reconstructed tracks. Then, the vertex seed and its surrounding tracks are used in the adaptive vertex fitting algorithm [145] for determining the vertex position. Tracks incompatible with the found vertex is used to seed another vertex, and the finding procedure is repeated until all tracks are associated to vertices, each required to have at least two associated tracks. Out of the multiple primary vertices found by these procedures, one vertex with the highest sum of associated track p_{T} is considered as the “hard-scatter” vertex and is used as the reference point of object calibrations.

4.3 Topo-cluster

Particle energy measurement in the calorimeters are performed for each three-dimensional “topo-cluster”, which is a cluster of topologically connected calorimeter cell signals [146]. The formation of topo-clusters is performed by a three dimensional growing-volume algorithm starting from a seed cell with high energy deposit. Neighboring cells of the seed cell are added to the cluster if the cell signal has a energy deposit exceeding two times the expected noise signal. The neighboring cells are then considered as the seed cells for the next iteration of the growth. The growth continues until the all cells exceeding the threshold are collected. If two growing clusters overlap, they are merged into one cluster. The cluster formed by the this algorithm could be too large to provide precise measurement of the particle energy. Hence, cluster splitting is applied if there are two or more local signal maxima defined by $E_{\text{cell}} > 500$ MeV.

4.4 Jet

Reconstruction and calibration

Gluons and quarks produced by the proton-proton interactions are reconstructed as groups of hadrons called “jets” as a result of hadronization. Jets are reconstructed using charged tracks and topo-clusters with dedicated algorithms. First using the particle flow algorithm [147], tracks and topo-clusters are matched accordingly, and cell-based energy subtraction is performed to remove overlaps between the momentum and energy measurements in the Inner Detector and calorimeters. Next, using the tracks originating from the hard-scatter vertex and topo-clusters surviving the energy subtraction in particle flow, jets are reconstructed using the anti- k_t algorithm [148] with radius parameter $R = 0.4$.

Since the energy of the jets are reconstructed at electromagnetic scale, jet energy scale calibration [149] is performed to correct the measured jet energy. Fig. 4.2 shows the stages of jet energy scale calibrations. Pileup corrections are first conducted to subtract contributions of pileup from the jet p_T . This is followed by the absolute MC-based calibration, which corrects the reconstructed jet four-momentum to the particle-level energy scale, considering detector response effects. Global sequential calibration is later performed to reduce dependencies on the initiating and constituent particles. Finally, in situ calibrations are applied to data to correct for the differences between data and MC.

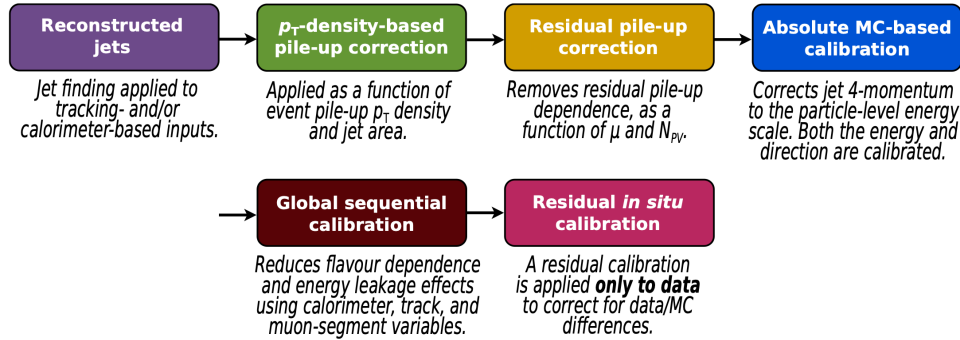


Figure 4.2: Stages of jet energy scale calibrations [149].

Jet vertex tagging

Pileup mitigation is necessary to suppress jets which do not originate from the hard-scatter event. For the jets used in the analysis, jet vertex tagging (JVT) [150] is applied for this purpose. JVT is constructed using a two-dimensional likelihood in the corrected jet vertex fraction (corrJVF) and R_{p_T} plane. The corrJVF variable is defined as the scalar p_T sum of the tracks associated with the jet and originate from the hard-scatter vertex (PV₀), divided by the scalar p_T sum of the associated tracks that originate from all interactions including pileup [150]:

$$\text{corrJVF} = \frac{\sum_i p_T^{\text{trk}_i}(\text{PV}_0)}{\sum_i p_T^{\text{trk}_i}(\text{PV}_0) + \frac{1}{\kappa \cdot n_{\text{trk}}^{\text{PU}}} \sum_{n \geq 1} \sum_i p_T^{\text{trk}_i}(\text{PV}_n)}. \quad (4.1)$$

Here, PV_n ($n \geq 1$) denotes primary vertices of pileup interactions. For correction of the linear increase of pileup p_T^{trk} with the total number of pileup tracks per event $n_{\text{trk}}^{\text{PU}}$, the pileup term is divided by a factor of $(\kappa \cdot n_{\text{trk}}^{\text{PU}})$ with $\kappa = 0.01$. On the other hand, R_{p_T} is defined as

$$R_{p_T} = \frac{\sum_i p_T^{\text{trk}_i}(\text{PV}_0)}{p_T^{\text{jet}}}, \quad (4.2)$$

where p_T^{jet} is the fully calibrated jet p_T [150]. Using the two-dimensional likelihood, the JVT is capable of separating hard-scatter jets and pileup jets as shown in Fig. 4.3.

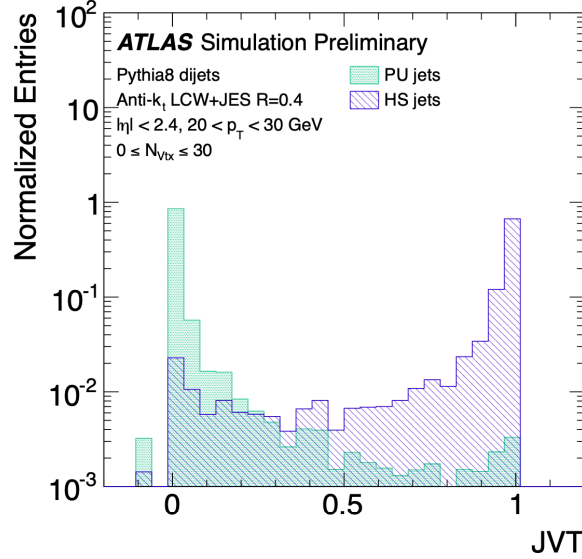


Figure 4.3: Distributions of JVT score for hard-scatter jets and pileup jets, evaluated with dijet samples [150].

Flavor tagging

Jet flavor tagging plays a significant role in identifying physics processes. In particular, separation of jets containing b -hadrons and c -hadrons (b - and c -jets) from light-flavor jets (u -, d -, and s -jets) and gluon jets is of high importance. In this search, flavor tagging is used to veto events with b -jets to suppress $t\bar{t}$ backgrounds.

Flavor tagging algorithms exploit the long lifetime of b - and c -hadrons, generally resulting in a displaced secondary vertex, few mm away from the hard-scatter primary vertex. First, low-level algorithms reconstruct the characteristics of b - and c -jets using properties of tracks and displaced vertices. IP2D and IP3D [151] are low-level algorithms which use the impact parameters of individual tracks associated with the jets. RNNIP algorithm [152] uses recurrent neural networks (RNNs) to further consider the correlation of impact parameters between tracks; if one track has a large impact parameter, it is likely that other associated tracks also have large impact parameters. SV1 [153] is a secondary vertex tagging algorithm that reconstructs a displaced secondary vertex within a jet, using a χ^2 test. JetFitter [154] uses a modified Kalman filter [143] to reconstruct the full b - and c -hadron decay chain by exploiting the topological features within the jet.

The subsequent high-level algorithm combines the outputs of the low-level algorithms using multivariate classifiers. This search uses the **DL1r** algorithm [155], which combines the results of **IP2D**, **IP3D**, **RNNIP**, **SV1**, and **JetFitter**, using a fully connected NN. The **DL1r** NN outputs the probabilities for a jet to be a b -jet, a c -jet, or a light-flavor jet, defined as p_b , p_c , and p_{light} , respectively.

This search uses b -jet tagging to veto events with b -jets, mainly to suppress $t\bar{t}$ processes. The final discriminant of b -tagging is defined as

$$D = \ln \left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\text{light}}} \right), \quad (4.3)$$

where f_c is the effective c -jet fraction, optimized to 0.018. Fig. 4.4 shows the b -jet tagging efficiency for various working points. This search uses the 85% working point, which the final discriminant D is fixed to a value for which 85% of the b -jets in a $t\bar{t}$ sample have a higher score.

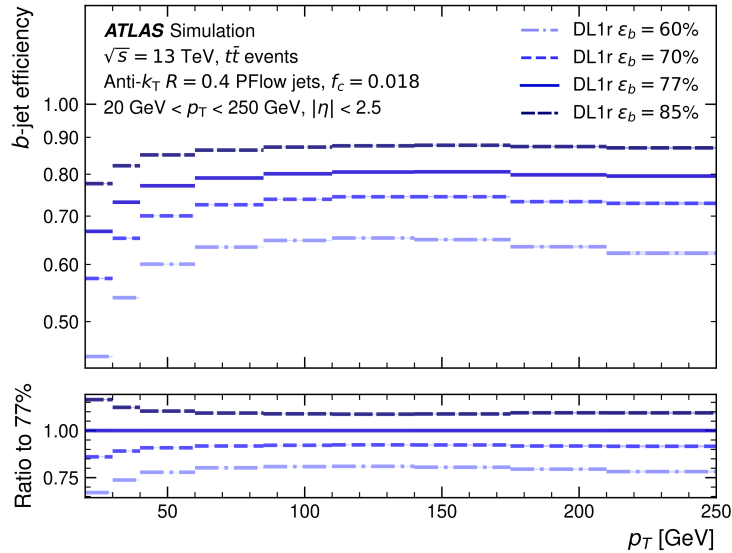


Figure 4.4: B -jet tagging efficiency for various working points as a function of b -jet p_T [155].

Jet cleaning

In searches using leading jets, imposing certain criteria on the quality of the jets help suppress non-collision background processes [156]. The implementation of these criteria are known as jet cleaning.

Good and fake jets can be discriminated using track and calorimeter based variables. In particular, the following variables are used. The jet charged fraction f_{ch} is defined as the scalar sum of the p_T of tracks, originating from the primary vertex associated to the jet, divided by the p_T of that jet. In addition, the energy fraction in the layer with maximum energy deposit in the calorimeters, denoted as f_{max} , is defined. The ratio between these variables, $f_{\text{ch}}/f_{\text{max}}$, is required to be small for good quality jets. In the *Tight* working point used in this search and later mentioned in Section 6.2, $f_{\text{ch}}/f_{\text{max}} < 0.1$ is required for jets with $|\eta| < 2.4$.

Preselection requirements in this search

The following preselection requirements are imposed to the jets used in the analysis.

- All jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$.
- For jets having $p_T < 60$ GeV and $|\eta| < 2.4$, $JVT > 0.5$ is required for pileup mitigation.
- B -jets are required to have $p_T > 20$ GeV and $|\eta| < 2.5$ and are identified using the DL1r 85% working point,

Further selection criteria used in the analysis are discussed later in Section 6.

4.5 Electron

When electrons pass through material, they radiate photons through Bremsstrahlung, and the generated photons create electrons through pair production, resulting in an electromagnetic (EM) shower. This mainly occurs in the EM calorimeter in the ATLAS detector, but could also occur more upstream, inside the Inner Detector. Thus, the reconstruction of electrons is performed using track and EM cluster information. Fig. 4.5 shows the path of an electron inside the ATLAS detector.

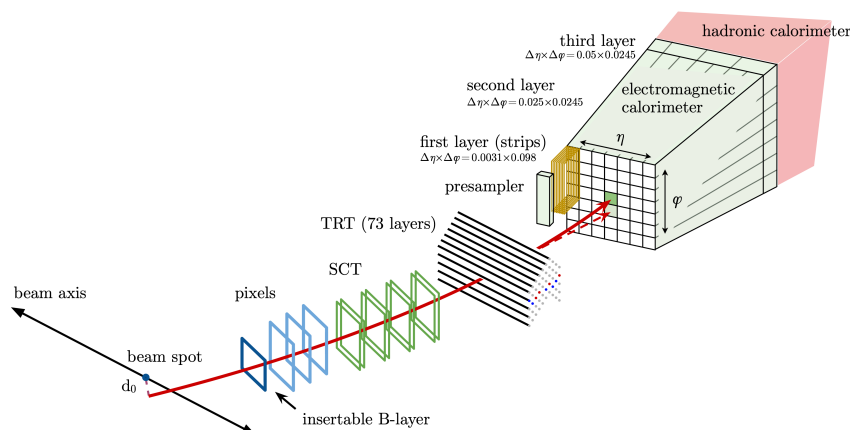


Figure 4.5: Schematic illustration of the electron path within the ATLAS detector [157].

Electron reconstruction starts off with seed-cluster reconstruction in the EM calorimeter. This is done using a sliding-window algorithm [158], which seeds energy cluster candidates from localized energy deposits by scanning over the whole EM calorimeter. The seed-cluster candidates are then matched to modified tracks, which account for the energy loss in material through an optimized Gaussian-sum filter (GSF) [159]. Finally, reconstructed clusters are formed around the seed clusters, and energy calibration is performed using multivariate algorithms [160].

Identification of electrons are performed using a likelihood-based (LH) method [157], which uses information from tracking, calorimetry, and combinations of both as inputs. The final discriminant for identification is formed by transforming the signal likelihood

fraction using an inverse sigmoid function. By setting fixed thresholds on this discriminant, three working points are defined for electrons with $E_T > 4.5$ GeV, as shown in Fig. 4.6: *Loose*, *Medium*, and *Tight*. The efficiencies for identifying a prompt electron with $E_T = 40$ GeV are 93%, 88%, and 80% for each of the working points, respectively. In addition, a variation of the *Loose* working point is defined by requiring a hit in the innermost layer of the Pixel detector and is called *LooseAndBLayer*.

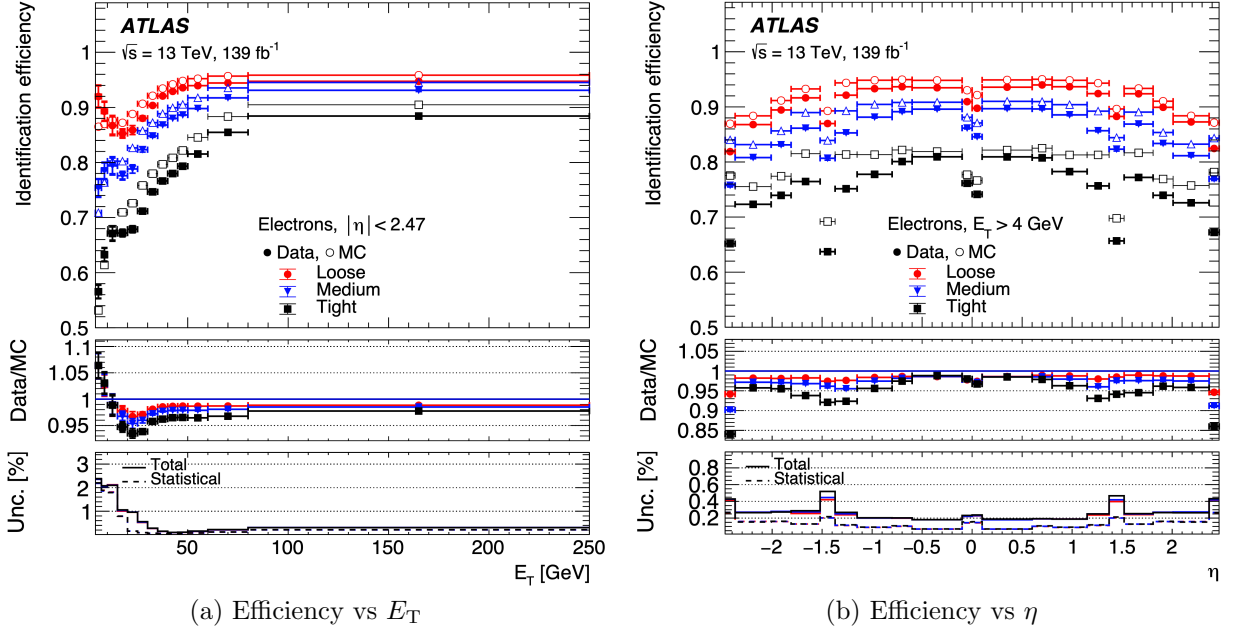


Figure 4.6: Electron identification efficiencies for various working points as a function of E_T and η [161].

Preselection requirements in this search

The following preselection requirements are imposed to the electrons used in this analysis.

- All electrons are required to have $p_T > 4.5$ GeV and $|\eta| < 2.47$.
- All electrons are required to pass the *LooseAndBLayer* identification working point.
- All electrons must have $|z_0 \sin \theta| < 0.5$ mm, likely originating from the hard-scatter vertex.

Further selection criteria used in the analysis are discussed later in Section 6.

4.6 Muon

Muon reconstruction is mainly based on information from the tracks in the Inner Detector and the measurements in the muon spectrometers [162, 163]. The matching between tracks in the Inner Detector and the tracks in the muon spectrometers is performed by a combined track fit based on the hits in both Inner Detector and muon spectrometers, also considering the energy loss in the calorimeters. This is done using an outside-in approach,

in which a muon reconstructed in the muon spectrometers is extrapolated inwards and matched to a track in the Inner Detector.

Muons are identified by imposing various requirements on features such as the number of hits in the Inner Detector and muon spectrometers, track fit properties, and variables defined to test the compatibilities between individual measurements in the Inner Detector and muon spectrometers. For instance, the q/p compatibility [163], defined as

$$q/p \text{ compatibility} = \frac{|q/p_{\text{ID}} - q/p_{\text{MS}}|}{\sqrt{\sigma^2(q/p_{\text{ID}}) + \sigma^2(q/p_{\text{MS}})}}, \quad (4.4)$$

is required to be small for muons, where $q/p_{\text{ID(MS)}}$ and $\sigma(q/p_{\text{ID(MS)}})$ represent the q/p and its uncertainty measured in the Inner Detector (muon spectrometers), respectively. Five identification working points are defined for muons with $p_T > 3$ GeV and $|\eta| < 2.7$: *Loose*, *Medium*, *Tight*, *High- p_T* , and *Low- p_T* [163]. Fig. 4.7 shows the muon identification efficiencies for *Medium* and *Low- p_T* working points, specifically for low- p_T muons.

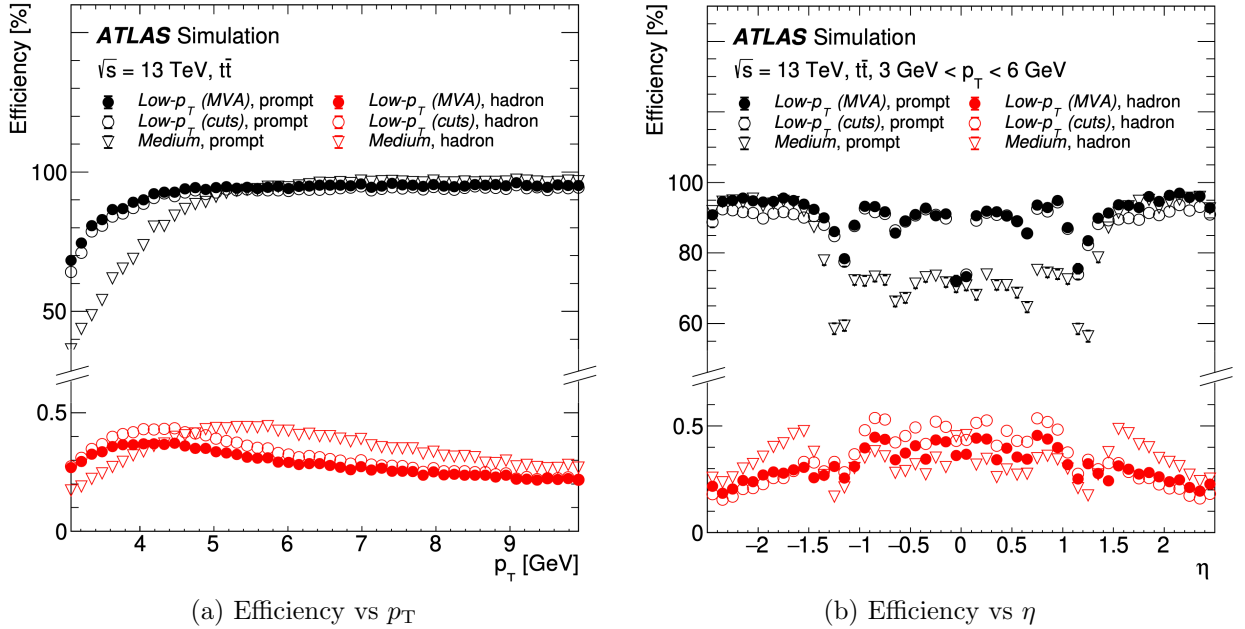


Figure 4.7: Muon identification efficiencies for *Medium* and *Low- p_T* working points as a function of p_T and η , measured using $t\bar{t}$ samples [163]. For *Low- p_T* working point, two variants are shown: cut-based and multivariate. Hadron misidentification efficiencies are also shown for reference.

Preselection requirements in this search

The following preselection requirements are imposed to the muons used in this analysis.

- All muons are required to have $p_T > 3$ GeV and $|\eta| < 2.7$.
- All muons are required to pass the *Medium* identification working point to realize sufficient background suppression.
- All muons must have $|z_0 \sin \theta| < 0.5$ mm, likely originating from the hard-scatter vertex.

4.7 Overlap removal

Since the reconstruction of multiple physics objects are performed individually, this could potentially result in ambiguities and overlaps between objects. To avoid the “double-counting” of each object, these ambiguities are resolved by performing sequential procedures known as “overlap removal (OR)”. The removal procedures are carried out in the following order, using the angular distance between objects defined as $dR = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Note that overlap removals for photons and tau-leptons are not applied, because they are not explicitly used in the event selection described in Section 6.

Muon-electron OR

Reject the muon if its Inner Detector track is shared with an electron.

Jet-electron OR

Reject the jet if not a b-jet and $dR < 0.2$.

Electron-jet OR

Reject the electron if $dR < \min(0.4, 0.04 + 10 \text{ GeV}/p_T(e))$.

Jet-muon OR

Reject the jet if not a b -jet and $dR < 0.2$.

Muon-jet OR

Reject the muon if $dR < \min(0.4, 0.04 + 10 \text{ GeV}/p_T(\mu))$.

4.8 Missing transverse momentum

Particles that do not interact with strong or electromagnetic force will likely pass through the ATLAS detector without leaving any trace. These include SM particles such as neutrinos and BSM particles such as neutralinos. However, since the transverse momentum of the initial p-p collision system at the LHC is zero, they can be indirectly detected as missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ with its magnitude E_T^{miss} .

Missing transverse momentum is reconstructed as the negative vector sum of all visible objects, which consist of hard and soft objects. The hard objects are comprised of electrons (e), photons (γ), hadronically decaying tau leptons (τ_{had}), muons (μ), and jets (j). The term considering soft objects, often referred to as the soft term, consider additional contributions from charged tracks which are from the hard-scatter vertex and are unused in the reconstruction of other objects. Thus, the missing transverse momentum can be written as [164]

$$\mathbf{p}_T^{\text{miss}} = -\sum \mathbf{p}_T^e - \sum \mathbf{p}_T^\gamma - \sum \mathbf{p}_T^{\tau_{\text{had}}} - \sum \mathbf{p}_T^\mu - \sum \mathbf{p}_T^j - \mathbf{p}_T^{\text{soft term}}, \quad (4.5)$$

in which the sum over each object is taken over those passing certain criteria, specifically described in Ref. [164]. In addition, the missing transverse momentum used in the analysis is defined as the *Tight* working point, in which forward jets are required to satisfy $p_T > 30$ GeV.

5. Development of Low- p_T Lepton Track Identification

One of the main efforts of the search presented in this dissertation is the development of the low- p_T electron and muon track identification methods, which aim to identify the low- p_T electrons and muons emitted from the signal $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ decay. They serve significant roles in this search; as the emitted electrons and muons have very low- p_T as shown in Fig. 5.1, the sensitivity to higgsinos with target mass splitting values largely depends on the performance of these identification algorithms.

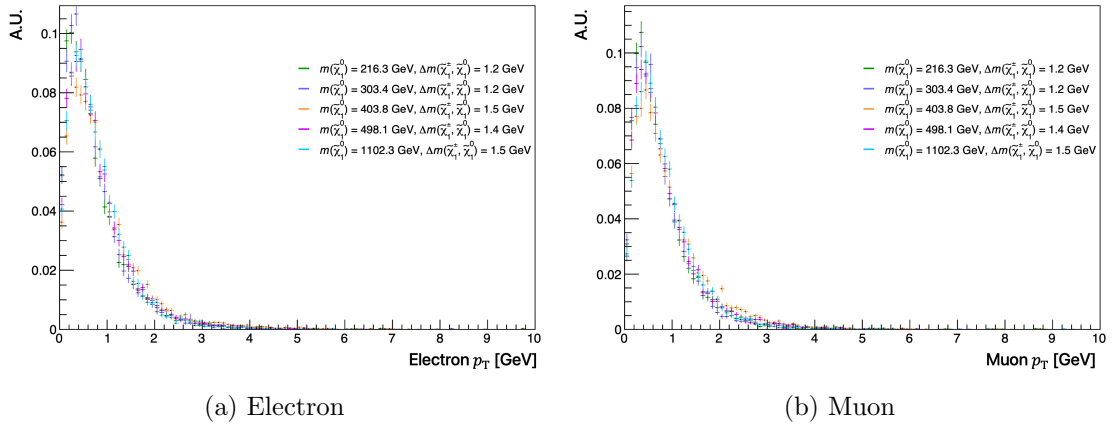


Figure 5.1: Truth p_T distributions of electrons and muons emitted from the higgsino through $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ decay. The distributions are shown for five different mass points, which have mass splitting values of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\text{--}3$ GeV. Most events have leptons having p_T below 1–2 GeV. No kinematic requirements have been imposed for the events used in these plots.

5.1 Low- p_T electron track

Standard electron identification algorithm described in Section 4.5 has a lower p_T threshold of 4.5 GeV to suppress hadronic noise in the calorimeters. However, target higgsino signals having a typical mass splitting $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of a few GeV tend to emit electrons (and muons, which is discussed later in Section 5.2) with lower p_T . Therefore, a new low- p_T electron track identification algorithm, dedicated to this search, has been newly developed. The new algorithm targets electron tracks having $p_T = 0.5\text{--}5$ GeV. This section describes the details of the low- p_T electron identification algorithm, its selection criteria, and its efficiency calibration.

5.1.1 Identification algorithm

The new low- p_T electron track identification (hereinafter referred to as LPET ID) targets tracks having p_T down to 0.5 GeV, which is the lower bound required for charged tracks. Considering that some of the electrons, having p_T larger but close to the 4.5 GeV threshold, escape the standard electron ID, the new LPET ID targets tracks having $p_T = 0.5\text{--}5$ GeV.

Tracks in the target p_T range is dominated by hadrons (mostly charged pions) and fake tracks. The idea of LPET ID is to distinguish electron-like tracks from these background tracks by exploiting their characteristics. The characteristics of tracks can be roughly categorized into two groups: silicon (Pixel and SCT) detector response and TRT detector response. Since the detector response of TRT has a large impact on electron identification as described in Section 2.2.3, its information is actively used for tracks with successful extension. In addition to this tracking information, energy deposits in the electromagnetic calorimeter are used by matching each track to the corresponding topo-cluster. LPET ID has been designed to utilize these track and calorimeter variables as inputs to classify electron-like tracks.

Track to calorimeter cluster position extrapolation

Although target tracks have very low p_T , the bulk is expected to reach the calorimeter in principle. It is therefore plausible to also use the calorimeter information as inputs of the LPET ID by extrapolating each track to its corresponding topo-cluster. The standard extrapolation method of tracks to the calorimeter has been briefly extended to support the target p_T range using a dedicated position matching method.

The basic idea of this method is to simply match the track to its corresponding cluster based on its relative position coordinates $\Delta\eta \equiv \eta_{\text{calo}} - \eta_{\text{track}}$ and $\Delta\phi \equiv \phi_{\text{calo}} - \phi_{\text{track}}$; a schematic diagram of the latter is shown in Fig. 5.2. Here, $(\eta_{\text{track}}, \phi_{\text{track}})$ and $(\eta_{\text{calo}}, \phi_{\text{calo}})$ correspond to the orientation of the particle at the interaction point and at the calorimeter, respectively. Considering the barrel and endcap topology of the calorimeters and also the curvature of electrons in 2 T magnetic field, candidate clusters for each track are required to pass the following loose position requirements:

- $|\eta_{\text{calo}} - \eta_{\text{track}}| < 0.1$,
- $\cos(\phi_{\text{calo}} - \phi_{\text{track}}) > 0.8$,
- $|\sin(\Delta\phi)_{\text{ext}}| < 0.2$, where

$$\sin(\Delta\phi)_{\text{ext}} \equiv \sin(\phi_{\text{calo}} - \phi_{\text{track}}) + 0.45 \cdot \frac{\text{trackCharge}}{\text{trackPt [GeV]}} \text{ (if } |\eta_{\text{track}}| < 1.5),$$

$$\sin(\Delta\phi)_{\text{ext}} \equiv \sin(\phi_{\text{calo}} - \phi_{\text{track}}) + \frac{2}{e^{1.13|\eta|} - e^{-1.13|\eta|}} \cdot \frac{\text{trackCharge}}{\text{trackPt [GeV]}} \text{ (if } |\eta_{\text{track}}| > 1.5).$$

The first requirement on $\Delta\eta$ simply requires the track and the calo cluster to be close to each other, whereas the second and third requirements on $\Delta\phi$ consider the electron track curvature in the plane perpendicular to the beampipe.

Cluster selection using energy deposits

In addition to the position requirements, cuts on the energy deposits of calorimeter layers are imposed to preselect electron-like topo-clusters, which tend to have more energy

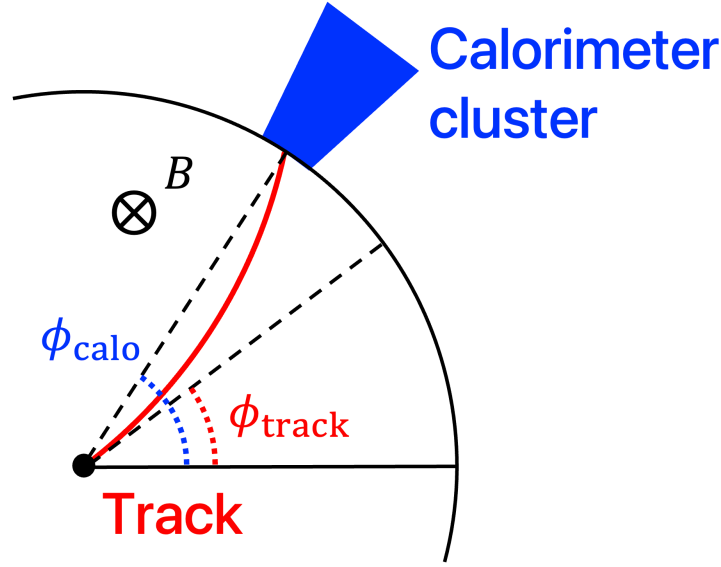


Figure 5.2: Schematic diagram of the curvature of the track and its corresponding calorimeter cluster, in the plane perpendicular to the beam pipe.

deposits in the EM layers, compared to the hadronic layers. To make the criteria independent of the electron energy, the cuts are imposed on the energy ratios $E_i/\Sigma_i E_i$ rather than the energy deposit E_i itself. Table 5.1 shows the list of calorimeter layers and their preselection requirements. Fig. 5.3 shows the energy ratio distributions of electron and background tracks in the first layers of the EM calorimeter. The values in Table 5.1 have been determined from these distributions.

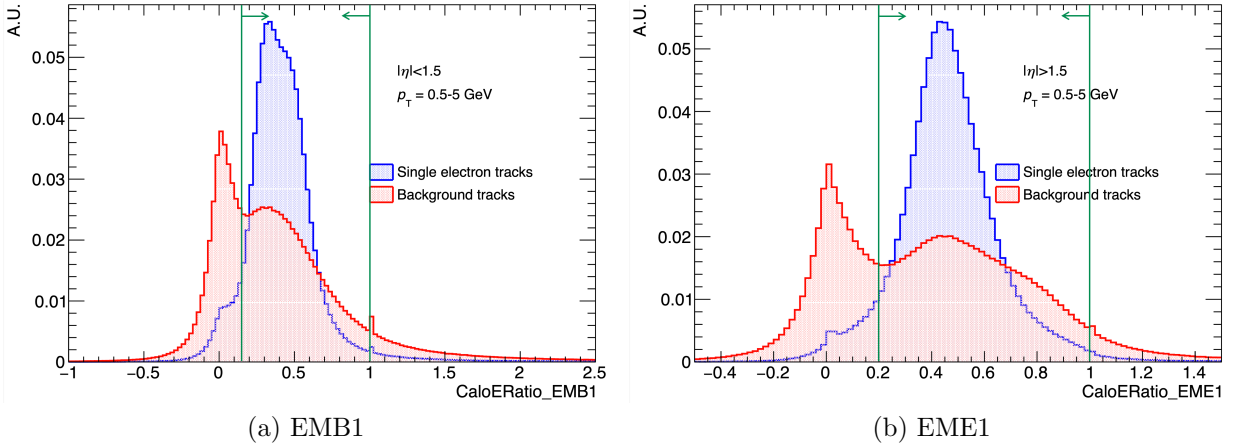


Figure 5.3: EMB1 and EME1 energy ratio distribution of topo-clusters passing the extrapolation requirements for electron tracks and background tracks. The energy ratio requirements in Table 5.1 have not been required for the clusters used in these plots, and the green lines indicate the selection requirements. Electrons tend to deposit more energy in the inner layer of the EM calorimeter.

Although there could be cases where multiple topo-clusters are associated to one track as shown in Fig. 5.4, for simplicity, a single cluster is selected for each track. For the training samples mentioned later in this section, this is achieved by selecting the preselected

Table 5.1: List of calorimeter layers and preselection cuts used for extrapolation of tracks to topo-clusters. Since raw energy values are used, the ratio values here could take negative values. The energy ratio value cuts for each layer are applied only when there is a corresponding energy deposit on that layer.

Layer name	Layer description	Energy ratio
PreSamplerB	Presampling layer of barrel EM calo	$[-0.1, 1.1]$ (if $ \eta_{\text{track}} < 1.5$)
EMB1	First layer of barrel EM calo	$[0.15, 1.0]$ (if $ \eta_{\text{track}} < 1.5$)
EMB2	Second layer of barrel EM calo	$[-0.1, 0.8]$ (if $ \eta_{\text{track}} < 1.5$)
EMB3	Third layer of barrel EM calo	$[-0.1, 0.1]$ (if $ \eta_{\text{track}} < 1.5$)
PreSamplerE	Presampling layer of endcap EM calo	$[-0.1, 0.55]$ (if $ \eta_{\text{track}} > 1.5$)
EME1	First layer of endcap EM calo	$[0.2, 1.0]$ (if $ \eta_{\text{track}} > 1.5$)
EME2	Second layer of endcap EM calo	$[0.05, 0.9]$ (if $ \eta_{\text{track}} > 1.5$)
EME3	Third layer of endcap EM calo	$[-0.05, 0.05]$ (if $ \eta_{\text{track}} > 1.5$)
HEC0	Zeroth layer of hadronic endcap calo	$[-0.2, 0.2]$ (if $ \eta_{\text{track}} > 1.5$)
HEC1	First layer of hadronic endcap calo	$[-0.5, 0.5]$ (if $ \eta_{\text{track}} > 1.5$)
HEC2	Second layer of hadronic endcap calo	-
HEC3	Third layer of hadronic endcap calo	-
TileBar0	Zeroth layer of barrel tile calo	$[-0.05, 0.05]$ (if $ \eta_{\text{track}} < 1.5$)
TileBar1	First layer of barrel tile calo	No deposit (if $ \eta_{\text{track}} < 1.5$)
TileBar2	Second layer of barrel tile calo	No deposit (if $ \eta_{\text{track}} < 1.5$)
TileGap1	First layer of tile calo gap	No deposit ($ \eta_{\text{track}} < 2.5$)
TileGap2	Second layer of tile calo gap	No deposit ($ \eta_{\text{track}} < 2.5$)
TileGap3	Third layer of tile calo gap	$[-0.05, 0.05], [0.95, 1.05]$
TileExt0	Zeroth layer of tile extended barrel calo	$[-0.05, 0.05]$ (if $ \eta_{\text{track}} < 1.5$)
TileExt1	First layer of tile extended barrel calo	No deposit ($ \eta_{\text{track}} < 2.5$)
TileExt2	Second layer of tile extended barrel calo	No deposit ($ \eta_{\text{track}} < 2.5$)

cluster having the smallest dR_{ext} defined as

$$dR_{\text{ext}} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi_{\text{ext}})^2},$$

where $\Delta\phi_{\text{ext}} \equiv \sin^{-1}(\sin(\Delta\phi)_{\text{ext}})$. Two-dimensional distributions of $\Delta\phi_{\text{ext}}$ vs $\Delta\eta$ are shown in Fig. 5.5. This simply requires the cluster to be the closest to the track, with curving trajectory and detector topology taken into account. However, this method is only used for the training and not used for the search; the preselected cluster having the highest LPET ID score is chosen for the search.

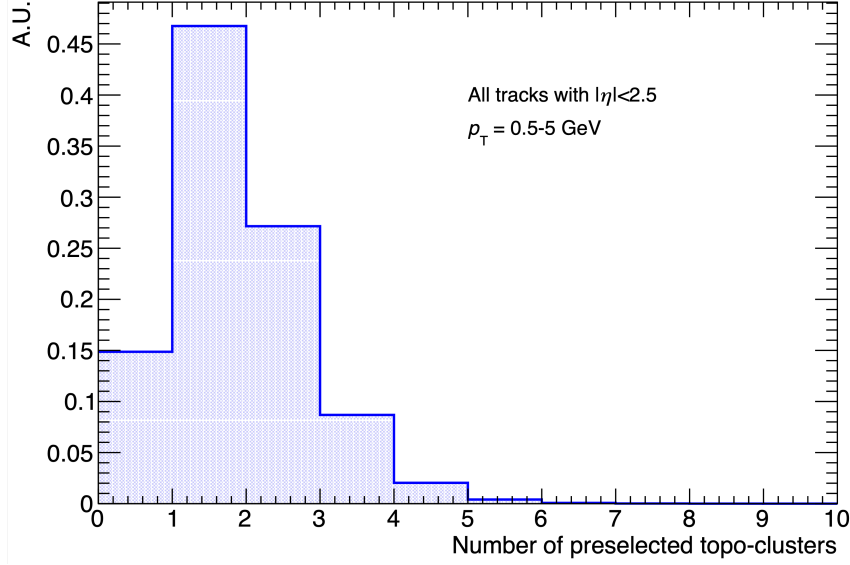


Figure 5.4: Simulated number of topo-clusters passing the position extrapolation and energy deposit preselection requirements, associated to an electron track reconstructed with pileup conditions similar to 2018 data. About 40 % of the electron tracks have two or more associated topo-clusters, and 15% of electron tracks do not have any associated topo-clusters.

Input features

The list of the input variables used for the LPET ID are shown on Table 5.2. The inputs are roughly categorized into three groups: track, TRT, and calo inputs. Track inputs are available for every track, whereas the TRT and calo inputs are available only when the extension to the TRT and to the calorimeter is successfully performed, respectively.

The distributions of these variables have been checked to select which variables to use as inputs to the LPET ID. It has been seen that the fitting error variables of track inputs, many of the TRT inputs, and the energy deposits in the inner calorimeter layers have high importances for discriminating low- p_T electron tracks against low- p_T background tracks.

Fig. 5.6 shows the distributions of fitting error variables of the track inputs. Due to effects of Bremsstrahlung, the fitting errors of the track position tend to be larger for electron tracks compared to background hadron tracks. It has also been seen that this effect is more apparent if tracks with the same “actual” (or *truth*) p_T are compared; electron tracks tend to have smaller reconstructed p_T due to Bremsstrahlung, resulting in larger values of fitting errors.

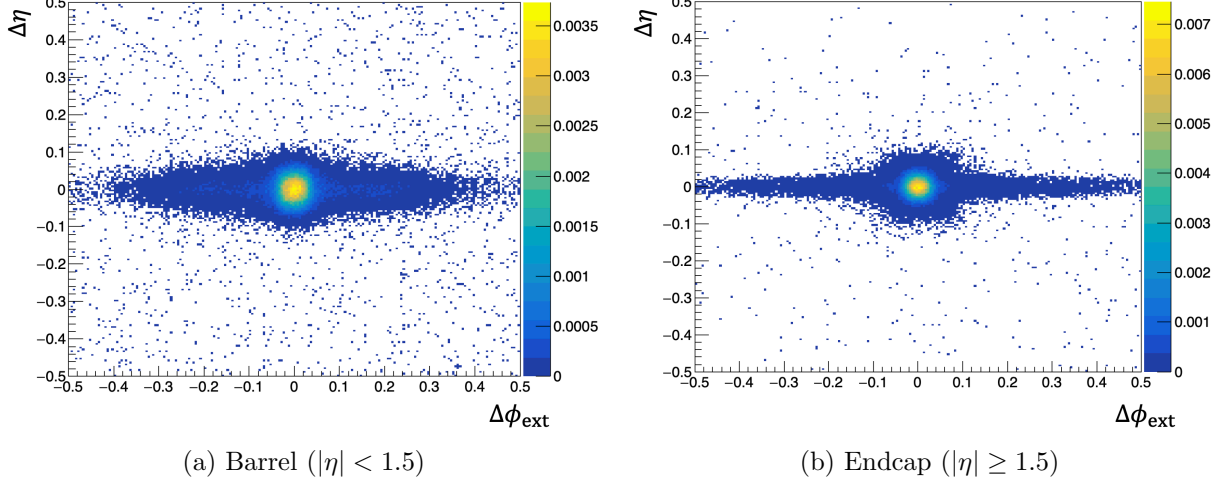


Figure 5.5: $\Delta\phi_{\text{ext}}$ vs $\Delta\eta$ distributions for simulated electron tracks having truth $p_T = 1$ GeV and reconstructed without pileup. The plots are shown separately for barrel and endcap regions. $\Delta\phi_{\text{ext}}$ and $\Delta\eta$ are both small for target electron tracks, motivating the requirement of small dR_{ext} .

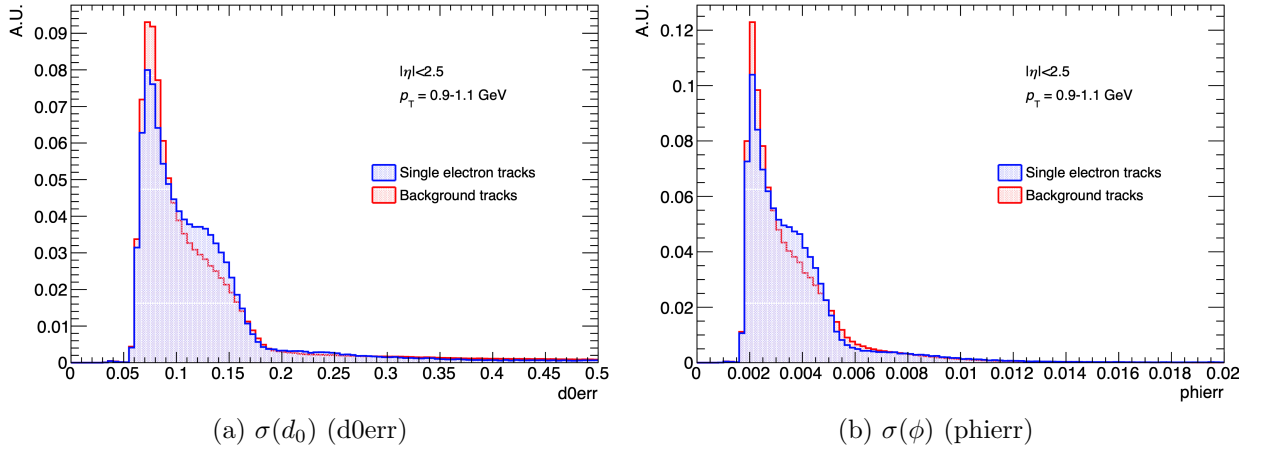


Figure 5.6: Distributions of fitting error variables of the track inputs. For tracks with $p_T = 0.9\text{--}1.1$ GeV, $\sigma(d_0)$ (d0err) and $\sigma(\phi)$ (phierr) are shown as examples. Error variables tend to be larger for electron tracks, due to effects of Bremsstrahlung.

Fig. 5.7 shows the distributions of TRT inputs with high importance. Many of the TRT inputs have strong separation power, since the TRT is capable of detecting transition radiation of the electrons, as described in Section 2.2.3. TRT hits with high transition radiation are detected as “high threshold hits”, and the number of such hits is larger for electrons. The probability of the track being an electron is also calculated from the high threshold hits as “eProbabilityHT”. Other TRT inputs such as dE/dx also have separation power.

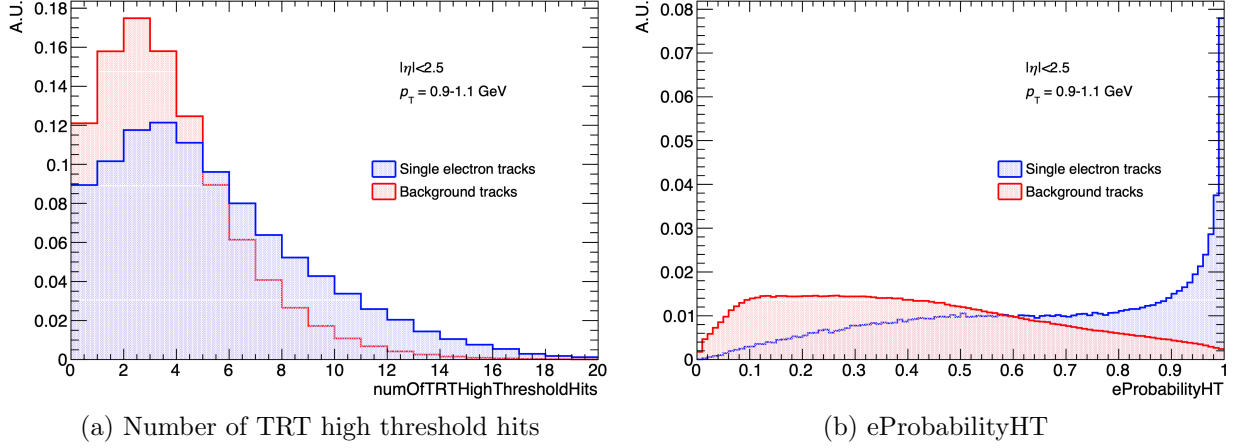


Figure 5.7: Distributions of TRT inputs. For tracks with $p_T = 0.9\text{--}1.1$ GeV, the number of TRT high threshold hits and eProbabilityHT are shown as examples. TRT inputs have strong separation power, because the TRT is capable of detecting transition radiation of the electrons.

Fig. 5.8 shows the distributions of energy deposit ratios in the inner layers of the EM calorimeter. The values of these variables tend to be larger for electron tracks compared to background tracks, because electrons are more likely to induce electromagnetic showers and deposit more energy.

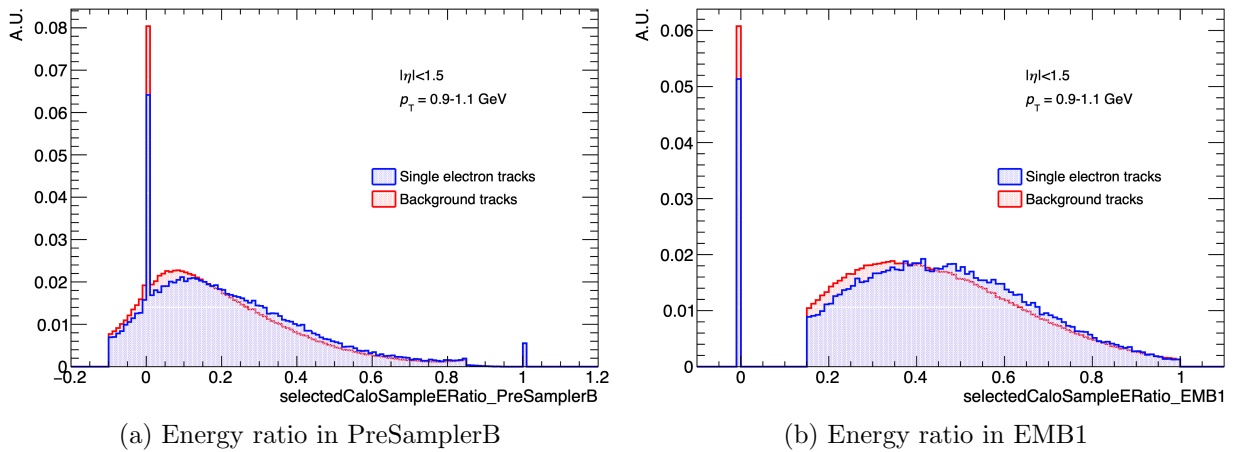


Figure 5.8: Distributions of calo inputs. For tracks with $p_T = 0.9\text{--}1.1$ GeV and $|\eta| < 1.5$, the energy deposit ratios in PreSamplerB and EMB1 are shown as examples. The energy deposit in the inner layers of the EM calorimeter tend to be larger for electron tracks compared to background hadron tracks.

Classification with deep neural network

A deep neural network (DNN) algorithm has been developed to maximize the identification efficiency of electron-like tracks by exploiting the track and its associated topo-cluster variables. Fig. 5.9 shows the overall structure of the LPET ID DNN. The algorithm binarily classifies whether the input track is electron-like or non-electron-like; an output electron likeliness score ranging from 0 to 1 is calculated based on the 79 input variables. The TRT variables and calorimeter variables may not be available for some tracks due to detector coverage and noise thresholds; in this case, these variables are set to 0. All of the input values are standardized according to the transformation

$$z = \frac{x - \mu}{\sigma}, \quad (5.1)$$

where x is the raw input value, μ is the average of that input in the training dataset, σ is the standard deviation of that input in the training dataset, and z is the standardized input used for the DNN.

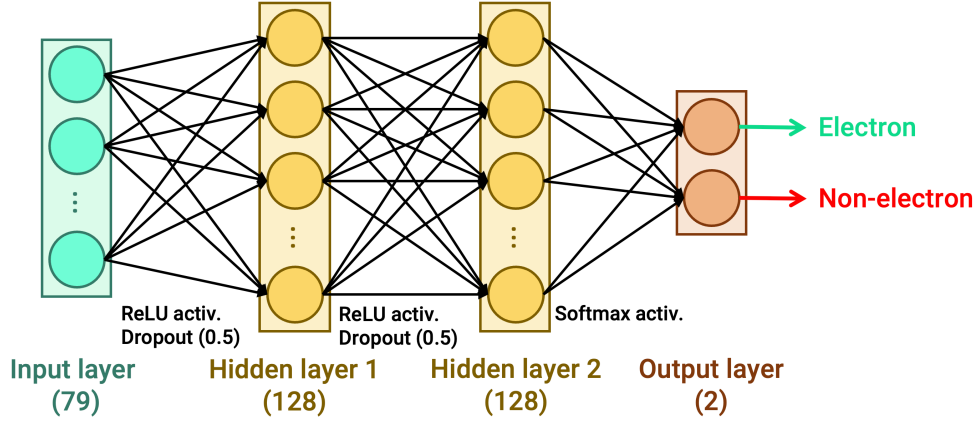


Figure 5.9: Overall structure of LPET ID DNN. 79 variables are used as inputs, and there are two hidden layers with 128 nodes. The nodes are fully connected. The output electron likeliness score ranges from 0 to 1, with 1 meaning that the track is fully electron-like.

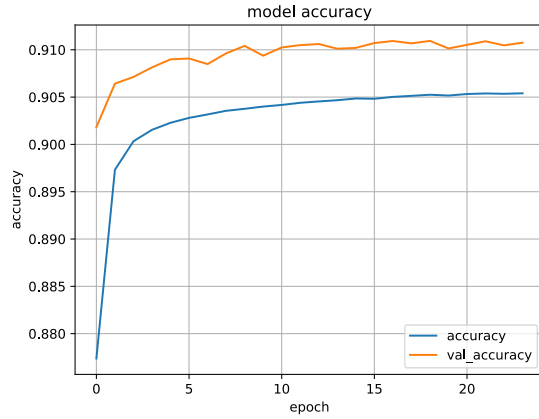
The training of LPET ID DNN has been done using MC “SingleParticleGun” electron events, where there is only one electron per event at the stage of event generation. To consider the effects of pileup collisions on track reconstruction in the training, the events were reconstructed by overlaying pileup collisions as described in Section 3.3.3. The signal electron tracks used for the training were sampled from these events by dR matching between the tracks and the truth electron particle. The background tracks used for the training were also sampled from these events by vetoing the dR matched signal tracks. For each signal and background tracks, about 4.5M samples were used for the training, where 10% were assigned as validation samples. The training configurations of the neural network; which have been optimized together with the model structure, are summarized in Table 5.3. The accuracy and loss values [165] during the training procedure are shown in Fig. 5.10; no overtraining has been observed.

Table 5.2: List of input variables used for LPET ID DNN.

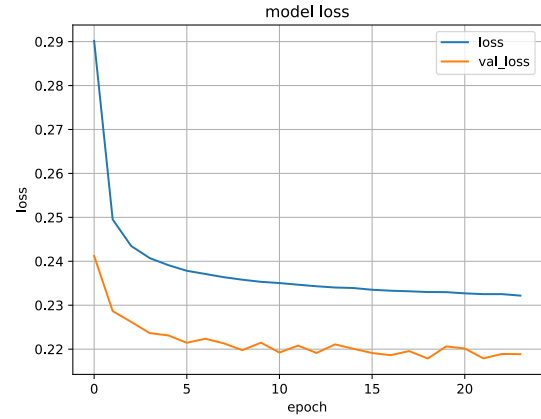
Track inputs	TRT inputs
charge	numOfTRTHighThresholdHits
chi2	numOfTRTHighThresholdHitsTotal
chi2OvernDoF	numOfTRTHighThresholdOutliers
d0	numOfTRTHits
d0err	numOfTRTOutliers
eProbabilityComb	numOfTRTSharedHits
eProbabilityHT	numOfTRTTubeHits
eta	numOfTRTXenonHits
expectIBLHit	TRTdEdx
expectBLayerHit	TRTdEdxUsedHits
hitPattern	TRTTrackOccupancy
nDoF	
numOfContribPixelLayers	
numOfGangedFlaggedFakes	
numOfGangedPixels	
numOfIBLOverflowsdEdx	
numOfIBLHits	
numOfIBLOutliers	
numOfIBLSharedHits	
numOfIBLSplitHits	
numOfIBLSpoiltHits	
numOfBLayerHits	
numOfBLayerOutliers	
numOfBLayerSharedHits	
numOfBLayerSplitHits	
numOfBLayerSpoiltHits	
numOfOutliersOnTrack	
numOfPixelDeadSensors	
numOfPixelHits	
numOfPixelHoles	
numOfPixelSharedHits	
numOfPixelSplitHits	
numOfPixelSpoiltHits	
numOfSCTDeadSensors	
numOfSCTDoubleHoles	
numOfSCTHits	
numOfSCTHoles	
numOfSCTOutliers	
numOfSCTSharedHits	
numOfSCTSpoiltHits	
numOfUsedHitsdEdx	
pixeldEdx	
phi	
phierr	
pt	
qOverP	
qoverperr	
stdDevOfChi2OS	
theta	
thetaerr	

Table 5.3: Summary of the training configurations of LPET ID DNN.

Hyperparameter	Value
Batch size	2048
EarlyStopping	Enabled (Patience = 5)
Learning rate	0.001
Loss type	Categorical crossentropy
Optimizer	Adam



(a) Accuracy



(b) Loss

Figure 5.10: Accuracy and loss values for each epoch of LPET ID DNN training. No overtraining has been observed. The differences between training and validation is due to the dropout applied during the training procedure.

Performance

The performance of LPET ID DNN has been briefly evaluated using signal and background tracks in MC higgsino production events; detailed evaluation is described in Section 5.1.2, after the definition of its selection criteria. For simplicity, a single mass point $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (153, 150)$ GeV and a single production channel $pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$ have been chosen. The signal tracks were sampled from these events by performing dR matching to the truth electron particles originating from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decays. The background tracks were sampled by vetoing the signal tracks in the same set of events. Fig. 5.11 shows the performance of LPET ID DNN evaluated using these signal and background tracks. Clear separation of signal and background tracks has been achieved in the target low- p_T regimes.

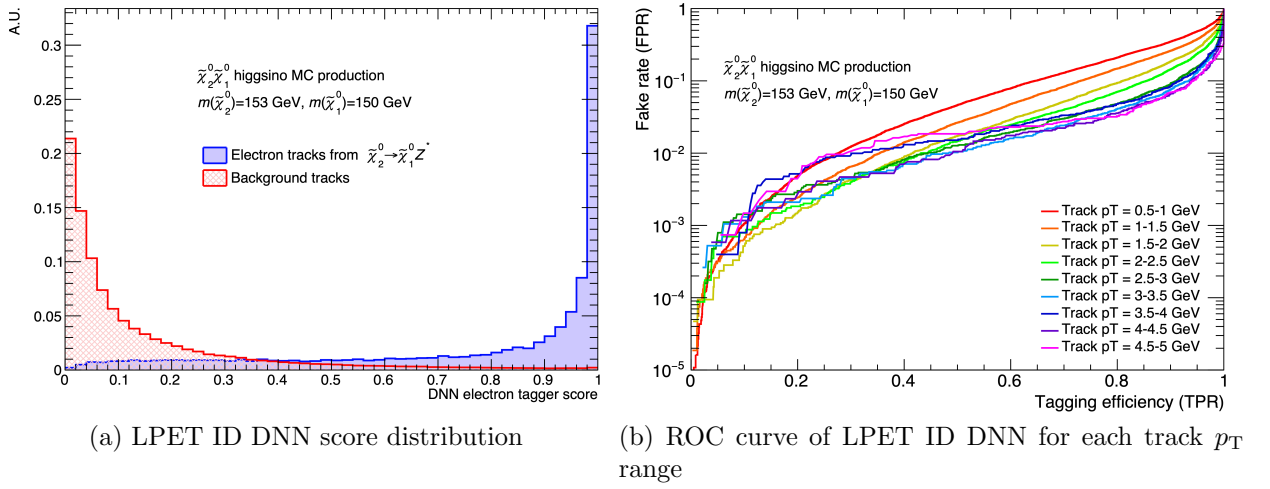


Figure 5.11: Performance of LPET ID DNN evaluated by signal and background tracks in higgsino production events. Clear separation of the signal and background tracks has been achieved.

5.1.2 Optimization of selection criteria

Because the LPET ID was trained using SingleParticleGun samples, it is necessary to adapt the LPET ID to the kinematics of the target signal. Therefore, optimized selection criteria targeting electron tracks from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay needs to be defined. Since the LPET ID DNN score may have some dependency on the track p_T and η , it is ideal to define criteria depending on these three variables. This section describes the criteria definition and the corresponding performance.

LPET ID WP DNN

To dynamically define selection criteria or “working point (WP)” dependent on the LPET ID DNN score, track p_T , and track η , another DNN algorithm (hereinafter referred to as LPET ID WP DNN) has been developed. Fig. 5.12 shows the overall structure of LPET ID WP DNN. The WP DNN is designed to binarily classify whether the input track is an electron coming from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay or not; an output score is calculated based on the three inputs. The inputs are standardized following Eq. (5.1).

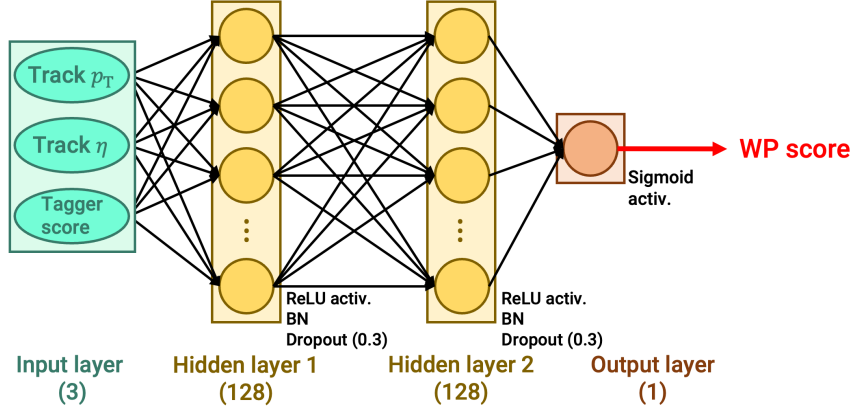


Figure 5.12: Overall structure of LPET ID WP DNN. Three variables are used as inputs: track p_T , track η and LPET ID DNN score. The structure is similar to that of LPET ID DNN, having fully connected nodes and two hidden layers with 128 nodes. The output WP score ranges from 0 to 1, with 1 meaning that the track is fully likely to be an electron from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay.

The training of LPET ID WP DNN has been done using MC events passing the 1L1T selection criteria mentioned later in Section 6. The signal electron tracks were sampled from higgsino production events by requiring dR matching between the tracks and the truth electron particle originating from $\tilde{\chi}_2^0$. All mass points and production channels mentioned in Section 3.3.1 have been used to ensure enough statistics and to achieve training compatible to all masses. The background tracks were sampled from W +jets events, which is the main SM background process of this search. All signal and background tracks are required to pass the track selection criteria also mentioned later in Section 6. For each signal and background tracks, 42k samples were used for the training, where 20% were assigned as validation samples. The training configurations of the WP DNN are summarized in Table 5.4. The distributions of the input variables are shown in Fig. 5.13.

Table 5.4: Summary of the training configurations of LPET ID WP DNN.

Hyperparameter	Value
Batch size	128
EarlyStopping	Enabled (Patience = 10)
Learning rate	0.0001
Loss type	Binary crossentropy
Optimizer	Adam

WP definition and performance

Fig. 5.14 shows the LPET ID WP DNN score distributions for test samples of signal and background tracks. By imposing a cut on this output score, it is possible to dynamically define a LPET ID WP targeting electron tracks from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decays. In the analysis, described later in Section 6, tracks having WP scores above 0.8 are considered to be signal tracks. Fig. 5.15 shows the LPET ID efficiency for this working point. The overall signal efficiency is 30–40%, while the background efficiency is about 0.5%.

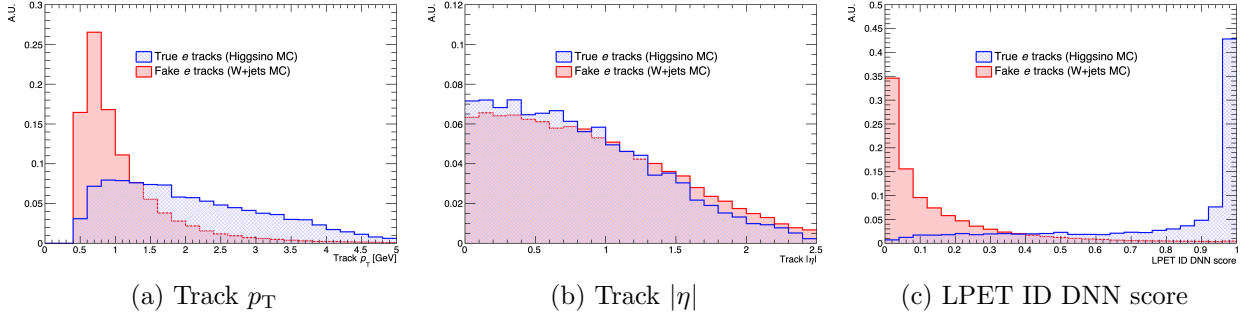


Figure 5.13: Input distributions of LPET ID WP DNN. The blue and red histogram represent signal tracks from higgsino MC and background tracks from $W + \text{jets}$ MC respectively.

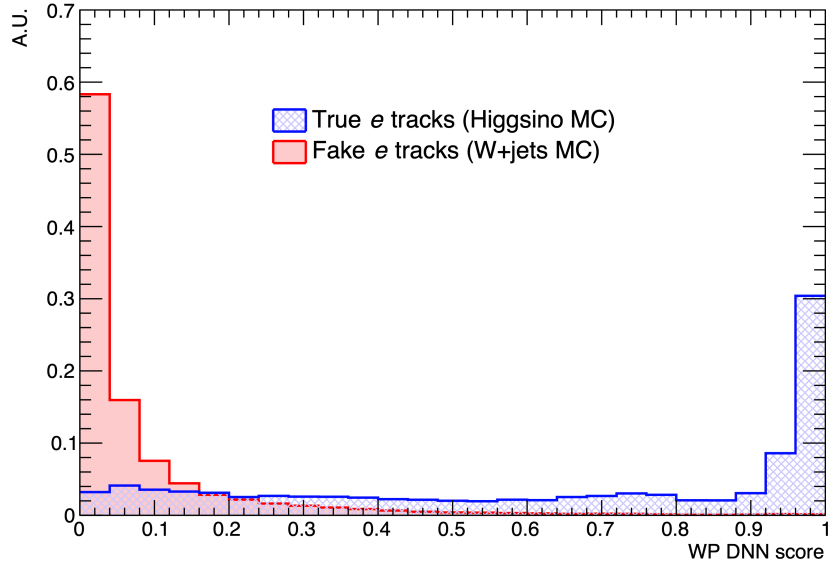


Figure 5.14: Output score of LPET ID WP DNN evaluated using test samples. The blue and red histogram represent signal tracks from higgsino MC and background tracks from $W + \text{jets}$ MC respectively. The WP used for the analysis is defined using this score.

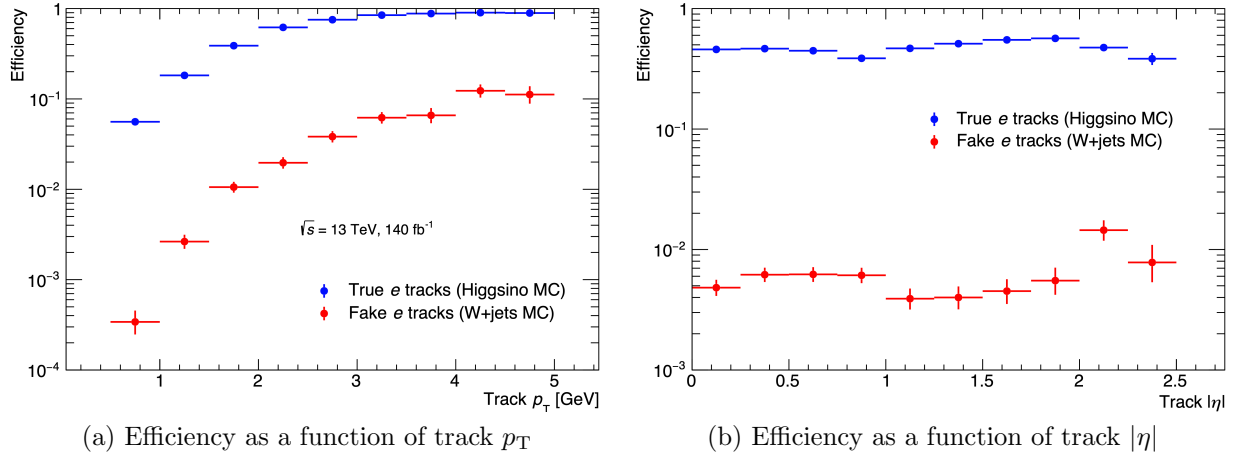


Figure 5.15: LPET ID efficiency of WP 0.8 for MC. The blue and red plots represent signal tracks from higgsino MC and background tracks from $W + \text{jets}$ MC respectively. The efficiency was evaluated for tracks passing the preselection used in the analysis.

5.1.3 Performance measurement with data and efficiency calibration

To apply the LPET ID WP in the analysis, its efficiency must be calibrated with data. This calibration has been done using $Z \rightarrow ee\gamma$ events. The section briefly summarizes the calibration method and its results.

Target event topology

For the calibration of LPET ID, a well-known SM process having a low- p_T electron track must be used as a control sample. $Z \rightarrow ee\gamma$ events are introduced for this purpose, considering its event topology with low background level. Fig. 5.16 shows a diagram representing $Z \rightarrow ee\gamma$ events. In this evaluation, only events with the following topology is targeted; the electron closer to the photon is required to have very low p_T , and the other electron and the photon take away most of the energy.

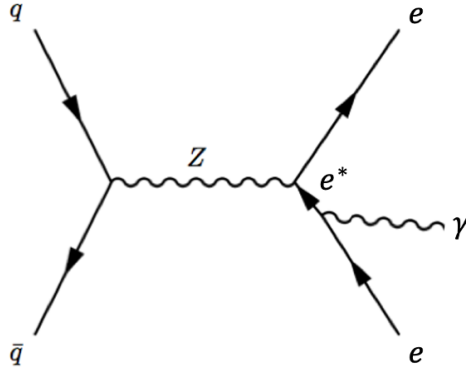


Figure 5.16: Diagram representing $Z \rightarrow ee\gamma$ events used for the calibration of LPET ID. The electron closer to the photon is required to have very low p_T for target events.

Event and track selection criteria

Events are selected using single electron trigger with trigger matching applied. $E_T^{\text{miss}} < 50$ GeV and b -tagged jet veto are required to suppress background events. A single electron and a single photon are required for each event; the electron must pass the *Tight* WP and have $30 < p_T < 60$ GeV, and the photon must pass the *Tight* WP and have $30 < p_T < 55$ GeV. Additional cuts on kinematic variables such as the electron-photon invariant mass $m(e, \gamma)$ and $dR(e, \gamma)$ are imposed to select $Z \rightarrow ee\gamma$ -like events.

Target tracks are required to pass the *TightPrimary* WP (defined in Section 4.1) and have charges opposite to that of the electron. Usual p_T and η requirements are applied: $0.5 < p_T < 5$ GeV and $|\eta| < 2.5$. Cuts on kinematic variables such as the track-photon invariant mass $m(\text{trk}, \gamma)$, $dR(\text{trk}, e)$ and $dR(\text{trk}, \gamma)$ are imposed to suppress background tracks as much as possible.

More details of the event and track selection criteria are summarized in Appendix B. All events and tracks passing these criteria are used for the LPET ID calibration.

Strategy and method for performance measurement

The events and tracks passing the selection criteria above are dominated by background. $Z \rightarrow ee\gamma$ consists only about 10% of the events passing the selection criteria. The remaining background events are mostly $Z \rightarrow ee$; one of the electrons fakes a photon. Tracks passing the selection criteria are dominated by hadronic tracks originating from underlying events for both $Z \rightarrow ee\gamma$ and $Z \rightarrow ee$ events. These “fake” electron track contributions can be inclusively considered as a single component. Therefore, the following discussion categorizes the events into only two components: “true electron” tracks having a low- p_T electron track which originate from $Z \rightarrow ee\gamma$ and “fake electron” tracks which do not.

To classify true and fake electron tracks in data, $dR(\text{trk}, \gamma)$ fit method has been introduced. As shown in Fig. 5.17, the shapes of $dR(\text{trk}, \gamma)$ distributions largely differ for true and fake electron tracks, because true electrons tend to be close to the photon, while fake electrons, mostly hadrons from underlying events, are randomly positioned relative to the selected photon for both $Z \rightarrow ee$ and $Z \rightarrow ee\gamma$ processes. The main strategy of the calibration is to fit these distributions for data using true and fake electron track templates retrieved from MC. The fit is performed independently for tracks passing and failing the LPET ID WP, respectively. Fig. 5.18 shows the post-fit distributions for tracks passing and failing LPET ID WP 0.8.

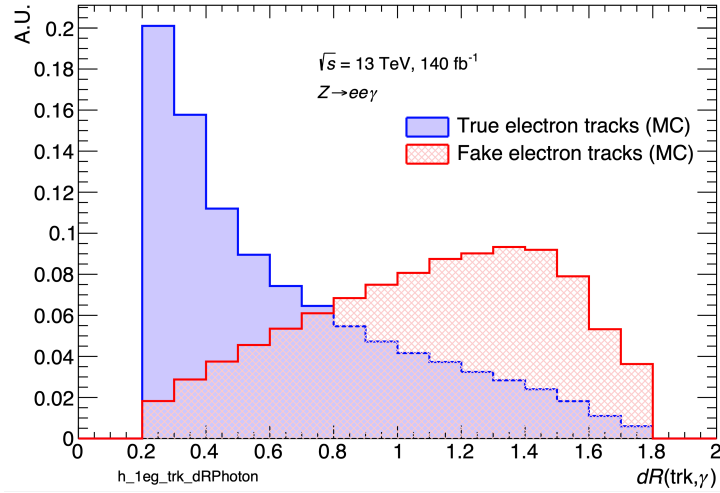


Figure 5.17: Normalized distributions of $dR(\text{trk}, \gamma)$ for true and fake electron tracks. True electrons only come from $Z \rightarrow ee\gamma$ events, while fake electron tracks also come from $Z \rightarrow ee$ events.

The efficiency of LPET ID WP for true electron tracks $\varepsilon_{\text{LPET ID}}^{\text{true}}$ can then be derived by integrating the post-fit distributions for both pass and fail tracks, namely,

$$\varepsilon_{\text{LPET ID}}^{\text{true}} = \frac{N_{\text{pass}}^{\text{true}}}{N_{\text{pass}}^{\text{true}} + N_{\text{fail}}^{\text{true}}},$$

where $N_{\text{pass}}^{\text{true}}$ and $N_{\text{fail}}^{\text{true}}$ are numbers of pass and fail true electron tracks counted by the integration. Since the LPET ID efficiency has strong dependence on track p_T as already shown in Fig. 5.15a, the fitting procedure is done for each track p_T bin.

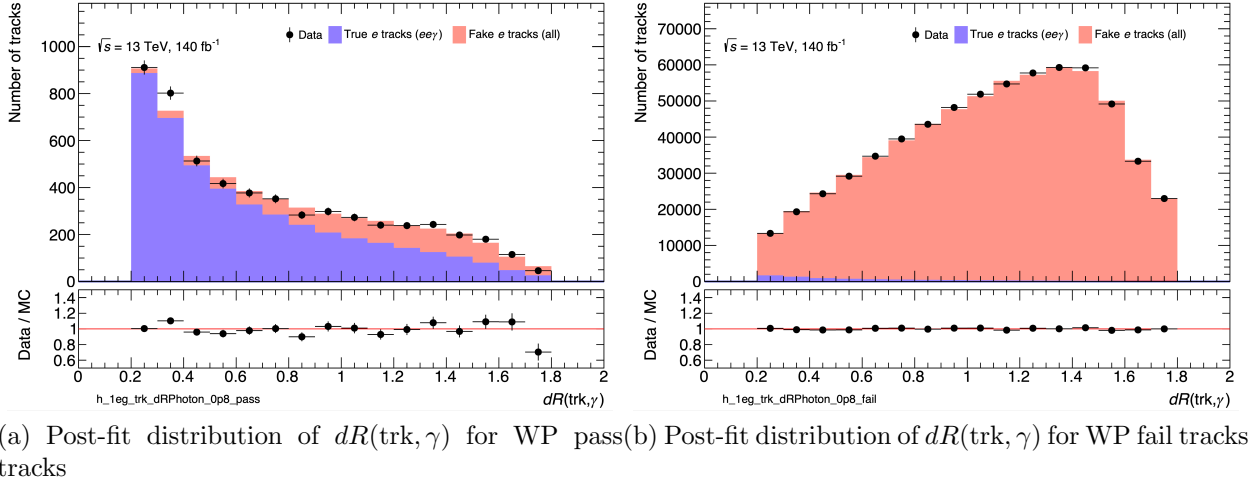


Figure 5.18: Post-fit distributions of $dR(\text{trk}, \gamma)$ for WP pass and fail tracks. The blue and red histograms represent the fitted distributions of true and fake electron tracks respectively.

Efficiency and scale factors

Fig. 5.19 shows the LPET ID WP efficiency and scale factors derived by $dR(\text{trk}, \gamma)$ fit method. Large discrepancies between data and MC is observed, leading to small scale factors. This is caused by poor MC modeling of input variables used for LPET ID DNN, such as the TRT variables. By applying the scale factors to signal and background MC tracks, these data/MC discrepancies of input variables are considered in an inclusive manner. In addition, the scale factors for fake electron tracks, shown later in Appendix B and not used in the analysis, have smaller values. Thus, the performance of LPET ID WP for data is expected to be better than MC in terms of true efficiency and fake rate.

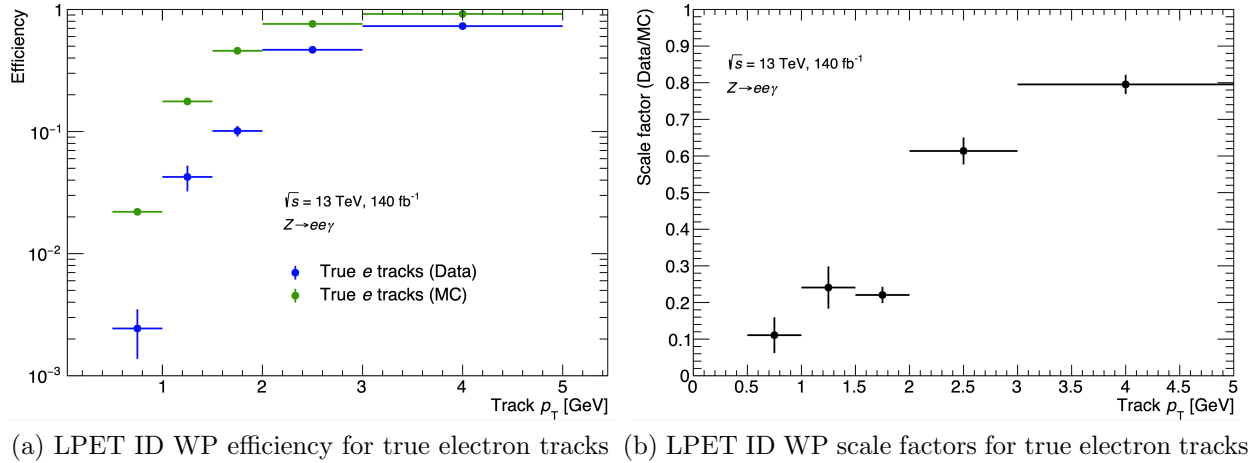


Figure 5.19: LPET ID WP efficiency and scale factors derived by $dR(\text{trk}, \gamma)$ fit method. The data efficiency is calculated by performing the fit for each track p_T bin. Scale factors are calculated by taking the ratio of data and MC efficiencies.

5.2 Low- p_T muon track

Similar to the low- p_T electron track identification in Section 5.1, a new algorithm has been developed for this search to identify low- p_T muon tracks eluding the standard identification algorithm described in Section 4.6. The contents summarized in this section are mainly from Ref. [166].

A muon loses about 3 GeV of its energy when traversing the ATLAS calorimeters as a minimum ionizing particle (MIP) [163]. Thus, standard muon identification described in Section 4.6 has a lower p_T threshold of 3 GeV as it requires hits in the muon spectrometers. The basic idea of the new low- p_T muon identification algorithm, called the Low- p_T Calo Tag (LCaT) muon algorithm, is to identify low- p_T muons that do not reach the muon spectrometers by exploiting the difference of energy deposits in the calorimeters. Such muons tend to stop within the outer layers of the calorimeters and behave as MIPs in those layers, leaving little energy. On the other hand, background hadrons such as pions induce hadronic showers and produce topo-clusters with large energy deposits. Fig. 5.20 shows the energy deposit distributions of muons and pions in the first layer of Tile calorimeter.

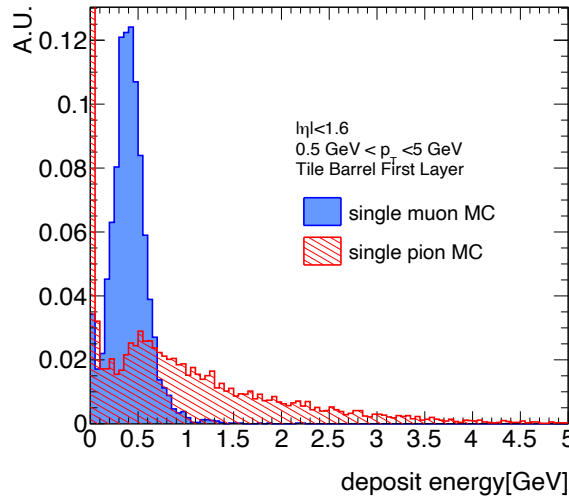


Figure 5.20: Energy deposit distributions for muons and pions in the first layer of the Tile barrel [166]. Muons have a peak around 0.5 GeV corresponding to MIP energy deposit, while the energy of pions is mostly distributed above that of a MIP.

The LCaT muon algorithm exploits track p_T , track η , and energy deposits in each of the layer of the topo-cluster by inputting them in a deep neural network. Thus, track and topo-cluster matching is required, which has been performed by a method similar to that described in Section 5.1.1. The neural network has been trained using signal muons and background particles in $J/\psi \rightarrow \mu\mu$ MC samples. The output muon likeliness score ranges from 0 to 1 and is referred to as the LCaT DNN score.

A working point (WP) dedicated to the search for higgsinos has also been defined by a neural-network-based method, similar to that mentioned in Sec. 5.1.2. The LCaT muon DNN score, track p_T , and track η are input into the LCaT muon WP DNN to output a single WP score (LCaT muon WP score). The WP DNN has been trained with signal muon tracks in higgsino MC and background tracks in W +jets MC. As shown in Fig. 5.21, LCaT muon WP score larger than 0.6 is required in the analysis. Fig. 5.22 shows the

efficiency for this working point as a function of track p_T . For p_T above 1.5 GeV, the signal efficiency is above 50%, while the efficiency for non-muon tracks is kept below 2%.

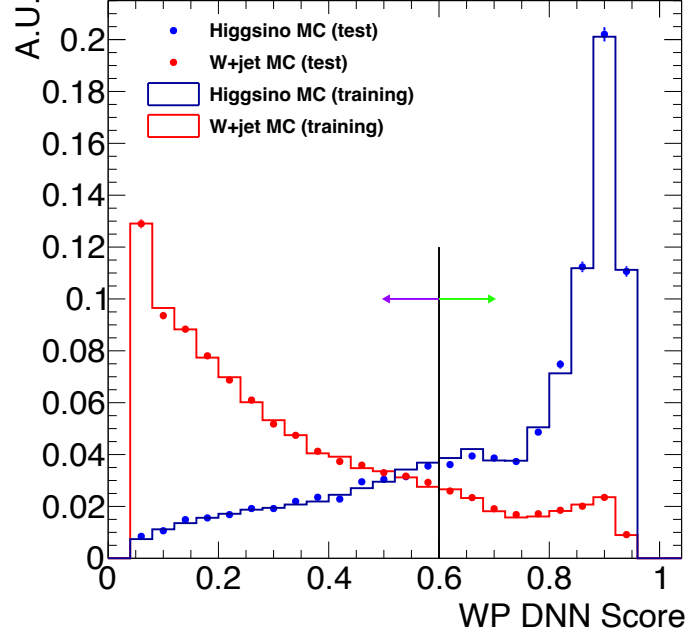


Figure 5.21: WP DNN score distributions for signal muon tracks in higgsino MC and background tracks in W +jets [166]. The blue dots and histogram are the distributions of test and training of LCaT DNN scores for signal muons in higgsino MC, respectively. Similarly, the red dots and histogram are for non-muon tracks in W +jets MC. There are no significant differences between test data and training data; no overtraining is observed.

The calibration of the LCaT muon ID has been conducted by targeting the process of J/ψ decay to two muons. In particular, tag and probe method was adopted to evaluate the efficiency of the LCaT muon ID for both data and MC. Target events are required to pass the single muon trigger, and the trigger matched muon is considered as the tag muon. The distribution of invariant mass of the tag muon and the probe muon is fit using crystal ball and quadratic functions to calculate the efficiency of LCaT muon ID for probe muons. The efficiencies and scale factors obtained from this calibration method are shown in Fig. 5.23. The scale factors are applied in this search to correct for the discrepancies observed between data and MC, which are mostly within 10% for all p_T and η regions.

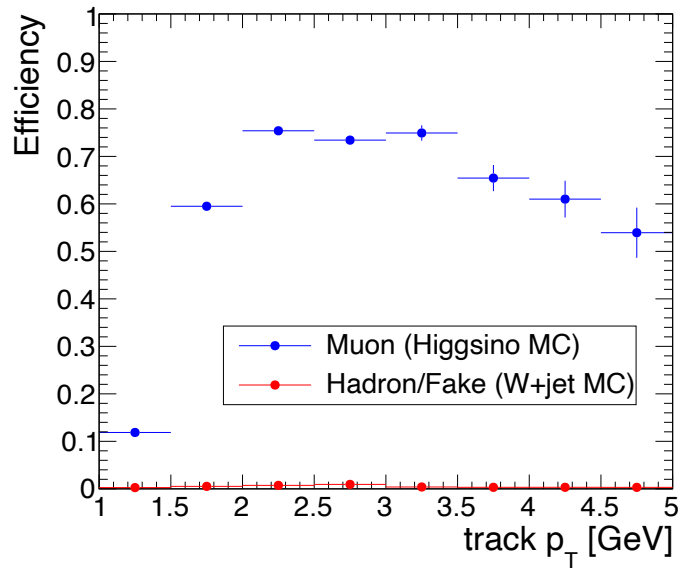
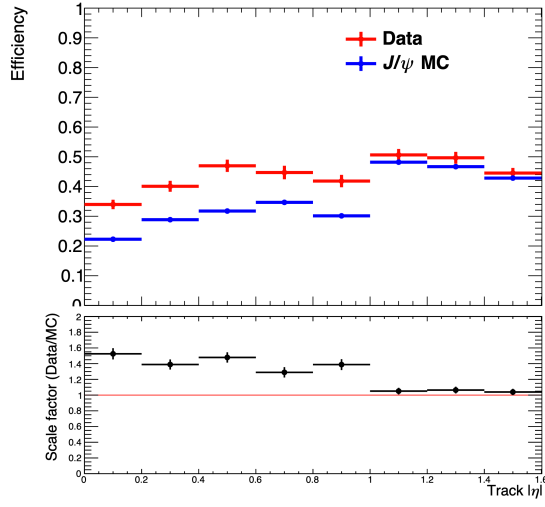
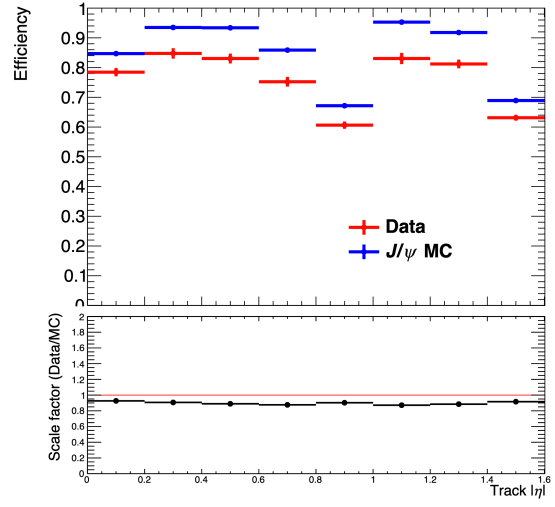


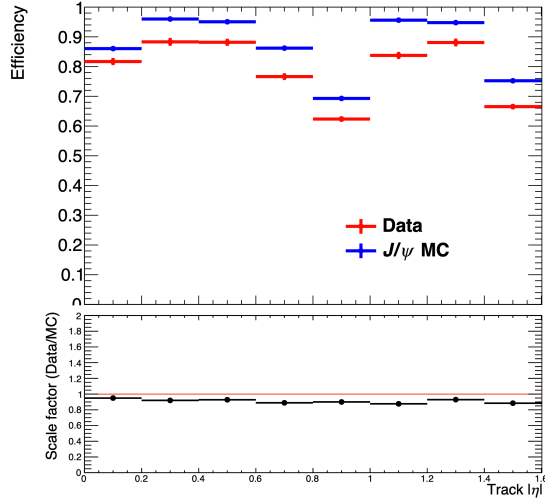
Figure 5.22: LCaT muon ID efficiency in higgsino MC and W +jets MC when WP threshold is set to 0.6 [166]. The blue histogram shows the identification efficiency for signal muons in higgsino MC. The red histogram is the identification efficiency for non-muon tracks in W +jets MC. High efficiency of signal muon tracks is realized in the low- p_T region, while the efficiency for non-muon tracks is kept below 2%.



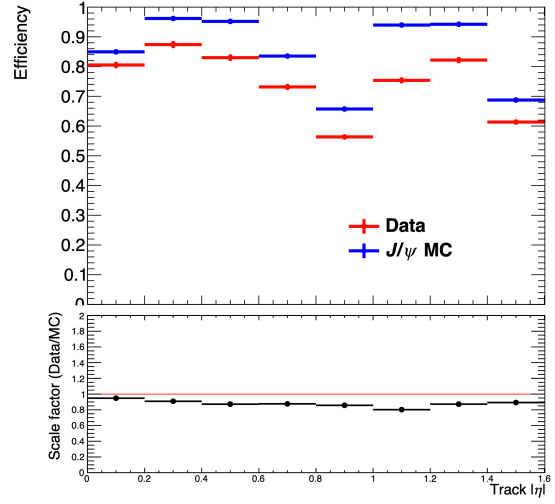
(a) $1.0 < p_T < 2.0$ GeV



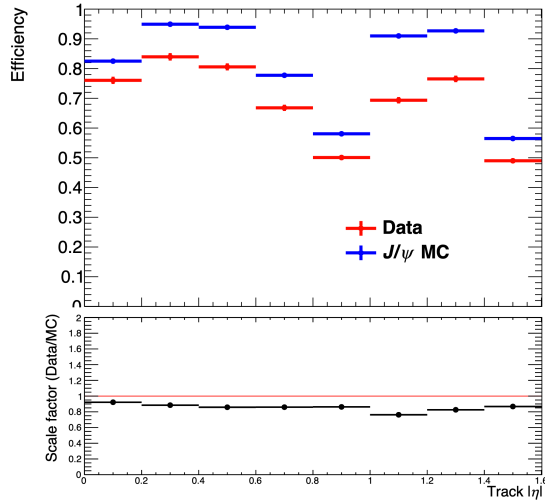
(b) $2.0 < p_T < 2.5$ GeV



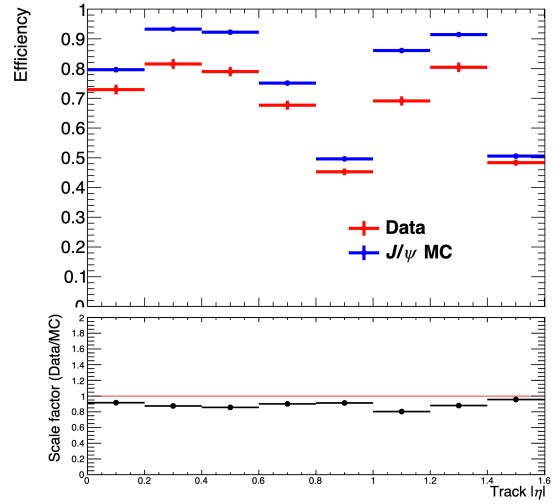
(c) $2.5 < p_T < 3.0$ GeV



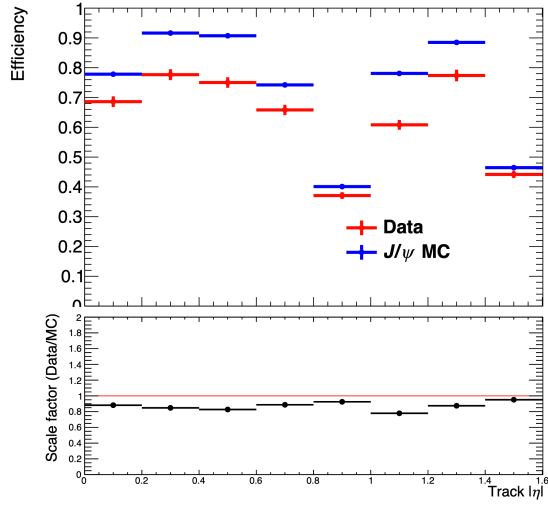
(d) $3.0 < p_T < 3.5$ GeV



(e) $3.5 < p_T < 4.0$ GeV



(f) $4.0 < p_T < 4.5$ GeV



(g) $4.5 < p_T < 5.0$ GeV

Figure 5.23: The result of LCaT muon ID efficiency measurement using tag and probe method. The red and blue histograms in the upper figure show the LCaT muon ID efficiency in J/ψ data and MC, respectively. The bottom figure shows the ratio of the efficiencies, corresponding to the scale factors which are applied to the signal and background MC samples.

6. Event Selection

To maximize sensitivity towards SUSY models having higgsinos with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \sim \mathcal{O}(1)$ GeV, dedicated event selection strategies utilizing the low- p_T lepton track taggers, described in Sections 5.1 and 5.2, have been developed. This section describes the basic strategies of the analysis, preselection and variables used for the definition of the Signal Region, neural network used to define the final discriminant, and the Signal Region definition.

Two channels have been prepared for the analysis: electron channel and muon channel. As the event selection strategies are similar for the two channels, they are described in a parallel manner.

6.1 Analysis strategy

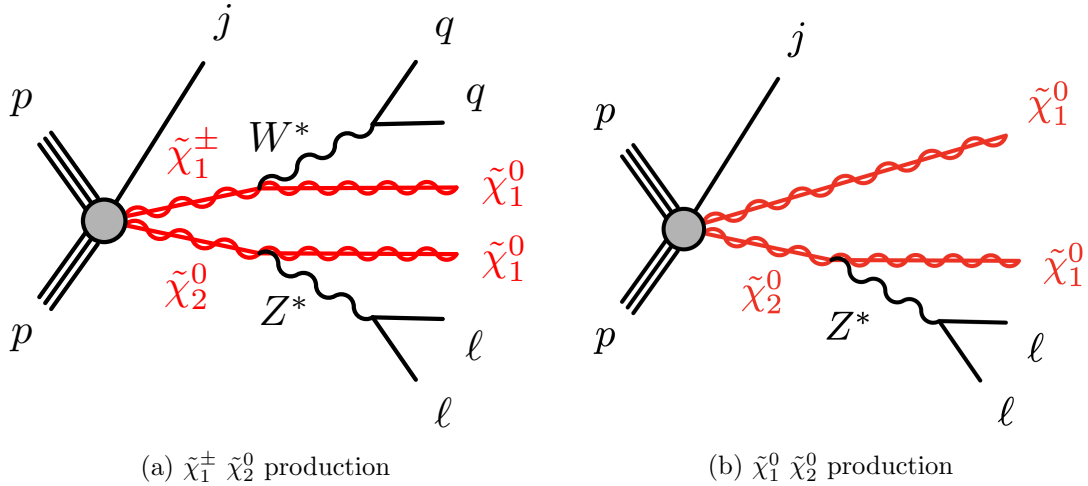


Figure 6.1: Diagrams of target signal processes. The j represents an initial state radiation jet. For $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, the off-shell W boson can also decay leptonically.

The main production processes of $\tilde{\chi}_2^0$ are shown in Fig. 6.1. In this search, events with $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay where the off-shell Z boson decays leptonically are targeted, as Z^* mass reconstructed from the two leptons, $m(Z^*) = m(\ell\ell)$, has significant separation power between signal and background processes as mentioned later in Section 6.2.2. $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production are both considered as signal processes. In the case of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, the decay process of $\tilde{\chi}_1^\pm$ is not specified: the off-shell W boson could decay hadronically or leptonically.

The signatures of these target processes could be observed in multiple detectors. First, with the requirement of R-parity conservation, $\tilde{\chi}_1^0$ are weakly interacting stable particles and are likely to traverse the ATLAS detector without leaving any signals. These are indirectly observed as missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ (defined in Section 4.8), however, if two $\tilde{\chi}_1^0$ are emitted back-to-back, the $\mathbf{p}_T^{\text{miss}}$ would cancel out and not be observed. Therefore, an initial state radiation (ISR) jet is required in this analysis to boost the target higgsino pair production system. In this case, the two $\tilde{\chi}_1^0$ are emitted in the same direction, opposite to the ISR jet, and could be observed as a high E_T^{miss} signature.

In addition, the features of the off-shell Z boson (Z^*) help in enhancing the sensitivity. The maximum value of the reconstructed Z^* mass equals the mass difference $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. Moreover, since the system including the Z^* is boosted by the ISR jet, Z^* is emitted in a direction close to the $\mathbf{p}_T^{\text{miss}}$.

In previous studies [109, 167], the identification efficiencies of low- p_T leptons were the bottleneck of the search. In the target $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of a few GeV, typical p_T of the emitted leptons are a few GeV, however, p_T thresholds of standard lepton identification are 4.5 GeV and 3 GeV for electrons and muons, respectively. This leads to very low acceptance of the target signal processes, thus limiting the sensitivity.

To overcome this difficulty, signal event efficiency is recovered by applying the newly developed low- p_T lepton track taggers: LPET ID to the electron channel and LCaT muon ID to the muon channel. In particular, these new taggers are applied to only one of the two leptons from Z^* ; standard identification is applied to the other lepton to realize sufficient background suppression. Hereinafter, **the low- p_T lepton identified with the standard method is referred to as the “ID lepton”**, while **the other low- p_T lepton identified with the newly developed method is referred to as the “lepton track”**.

Furthermore, the kinematics of the two leptons from Z^* are exploited. The two leptons are also boosted with the requirement of an ISR jet, which results in close-by ID lepton and low- p_T lepton track. The characteristics of the signal events are summarized in the following list, and a schematic diagram of a typical signal event is shown in Fig. 6.2.

- Objects
 - High E_T^{miss}
 - High- p_T ISR jet
 - 1 low- p_T ID lepton
 - 1 low- p_T lepton track
- Small angle between $\mathbf{p}_T^{\text{miss}}$ and Z^*
- Small Z^* invariant mass
- Small angle between ID lepton and lepton track

The flow of the analysis, described later in detail, is as follows. First, event preselection is applied to select events with a high- p_T hadronic jet, large missing transverse momentum, and one low- p_T ID lepton. Next, track selection is performed to select a single candidate low- p_T lepton track from many of the background hadronic tracks originating mainly from underlying events. Finally, the newly developed low- p_T lepton track identification method is applied to that candidate track to extract signal-like events.

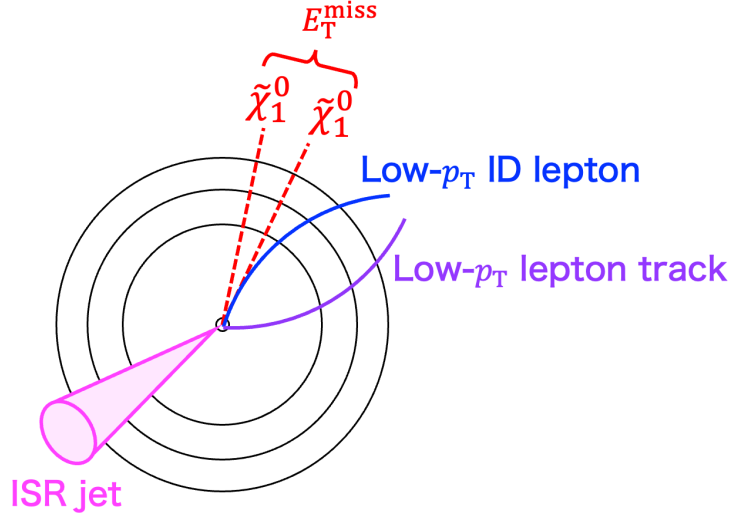


Figure 6.2: Schematic diagram of a signal event seen from the cross section of the ATLAS detector. An ISR jet is required to boost the target higgsino pair production system. The E_T^{miss} and the two leptons are objects originating from the boosted system.

6.2 Preselection and variables used to define the Signal Regions

Various requirements are imposed on distinctive variables of the event to discriminate signals from background events and to define the Signal Regions (SRs).

6.2.1 Event kinematic variables

Events are preselected with the following criteria, summarized in Table 6.1.

Table 6.1: Event kinematics preselection applied to all events in SR for the electron channel and the muon channel.

Variable	Electron channel	Muon channel
Trigger	E_T^{miss} trigger	
Offline E_T^{miss} [GeV]	> 200	
Leading jet p_T [GeV]	> 100	
Leading jet cleaning WP	<i>Tight</i>	
Number of b -jets	$= 0$	
Number of leptons	$= 1$ (electron)	$= 1$ (muon)
Lepton p_T [GeV]	< 10	
Lepton $ z_0 \sin \theta $ [mm]	< 0.5	
Lepton $ d_0/\sigma(d_0) $	< 5	< 3
Lepton identification WP	<i>Medium</i>	
Lepton isolation	No activities within $dR = 0.3$	

E_T^{miss} requirements

Signal events are expected to emit high E_T^{miss} due to two boosted $\tilde{\chi}_1^0$. Therefore, the search uses data collected by inclusive E_T^{miss} triggers. The offline E_T^{miss} is required to be above 200 GeV, which ensures the trigger to be at its efficiency plateau and be fully efficient, as described in Section 3.2.

Leading jet selection

In each event, the reconstructed jet with the highest p_T is identified as the leading jet. Leading jet p_T is required to be larger than 100 GeV to boost the higgsino pair production system. In addition, the leading jet is required to pass the *Tight* jet cleaning working point, aforementioned in Section 4.4, for the reduction of non-collision backgrounds.

Number of b -jets

B -veto is applied to suppress $t\bar{t}$ and single top backgrounds. It is required that the number of b -jets with p_T higher than 20 GeV be 0. The b -jets are identified with DL1r algorithm with a condition corresponding to 85% efficiency, as already mentioned in Section 4.4.

Number of leptons

Exactly one lepton is required to target signal events; one electron for the electron channel and one muon for the muon channel, where the preselection requirements have been described in Sections 4.5 and 4.6, respectively. This one lepton requirement assumes that the other lepton from Z^* decay fails the standard identification criteria, because it is expected to have very low p_T .

ID lepton selection

In addition to the preselection requirements, further criteria are required for the ID lepton to realize sufficient background suppression. Both the electron and the muon are required to pass the *Medium* working point and to be low- p_T : $p_T < 10$ GeV.

Promptness of ID lepton

For the target $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of a few GeV, the lifetime of $\tilde{\chi}_2^0$ is expected to be short enough for the lepton to be prompt. Therefore, $|z_0 \sin \theta| < 0.5$ mm is required for both leptons, and for the transverse impact parameter, $|d_0/\sigma(d_0)| < 5$ and $|d_0/\sigma(d_0)| < 3$ are required for electrons and muons, respectively.

Isolation of ID lepton

Signal leptons originating from Z^* are expected to have little surrounding activity compared to background leptons. Thus, the following “isolation” requirements are imposed. Within a cone of $dR = 0.3$, no charged tracks with $p_T > 1$ GeV associated to the hard-scatter vertex (excluding the track of the lepton itself) are allowed. However, if the later mentioned low- p_T lepton track candidate is within the cone, its contribution is subtracted to avoid vetoing signal tracks.

6.2.2 Variables used for low- p_T lepton track preselection

Candidate tracks, which the newly developed low- p_T lepton track ID will be applied to, are preselected by the following criteria. Events with no candidate tracks fail the event

selection and are not used in the analysis. The track preselection criteria are summarized in Table 6.2.

Table 6.2: Track preselection applied to low- p_T lepton candidate tracks for the electron channel and the muon channel.

Variable	Electron channel	Muon channel
Quality WP	<i>TightPrimary</i>	
Charge	Opposite of ID lepton	
p_T [GeV]	[0.5, 5]	[1, 5]
$ \eta $	< 2.5	< 1.6
$ z_0 \sin \theta $ [mm]	< 0.5	
$ d_0 $ [mm]	< 0.5	
Isolation	No activities within $dR = 0.3$	
$m(Z^*)$ [GeV]	< 3 , [3.2, 5]	
$dR(\text{lep}, \text{trk})$	[0.1, 1.4]	
$\Delta d_0(\text{lep}, \text{trk})$ [mm]	< 0.25	< 0.10
$\Delta z_0(\text{lep}, \text{trk})$ [mm]	< 0.30	< 0.26

Track quality and basic kinematic selections

First, the tracks must pass the *TightPrimary* working point described in Section 4.1. As the signal track comes from the Z^* decay, its charge is required to be opposite of that of the ID lepton. The required track p_T ranges are 0.5–5 GeV and 1–5 GeV for the electron and muon channel, respectively. For the track position, $|\eta| < 2.5$ and $|\eta| < 1.6$ are required for the electron and muon channel, respectively. These p_T and η requirements correspond to the LPET ID and LCaT muon ID target regions. In addition, impact parameter requirements are applied to both channels to target prompt lepton signals and to reject pileup track contributions: $|z_0 \sin \theta| < 0.5$ mm and $|d_0| < 0.5$ mm. For track isolation, a requirement similar to that of the ID lepton isolation is imposed: no charged tracks associated to the hard-scatter vertex are allowed within a cone of $dR = 0.3$, with the exception of the ID lepton to avoid vetoing signal tracks.

$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$

$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$ is the angular difference between the E_T^{miss} and Z^* , defined by

$$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*) = |\phi(\mathbf{p}_T^{\text{miss}}) - \phi(Z^*)|$$

in which $\phi(\mathbf{p}_T^{\text{miss}})$ and $\phi(Z^*)$ are the directions of missing transverse momentum and Z^* in ϕ . It is defined to be the absolute value of the angular difference, ranging from 0 to π . For signals, $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$ is expected to be small since both E_T^{miss} and Z^* originate from the higgsino pair production system boosted by the ISR jet. This variable is not used for the track preselection but is used as one of the inputs of the event selection neural network described later in Section 6.3. It also plays a significant role in the definition of regions used to validate the background estimation method, described later in Section 7.2.

$m(Z^*)$

The mass of the reconstructed off-shell Z boson $m(Z^*)$ has a peaking distribution with its maximum value at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. Therefore, the distribution of $m(Z^*)$ depends on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. $m(Z^*) < 5$ GeV is required for all scenarios since $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of the target scenarios are below 5 GeV. In addition, 3–3.2 GeV is rejected to veto tracks coming from J/ψ decays.

$dR(\text{lep}, \text{trk})$

$dR(\text{lep}, \text{trk})$ is the distance between the ID lepton and the lepton track defined by

$$dR(\text{lep}, \text{trk}) = \sqrt{(\eta_{\text{lep}} - \eta_{\text{trk}})^2 + (\phi_{\text{lep}} - \phi_{\text{trk}})^2}.$$

$dR(\text{lep}, \text{trk})$ also depends on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$; it is smaller for smaller mass splitting values. This is because Z^* with lighter mass tends to be more boosted, and the distribution of $m(Z^*)$ depends on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. $dR(\text{lep}, \text{trk}) < 1.4$ is required to target scenarios with mass splitting values below 5 GeV. On top of this, $dR(\text{lep}, \text{trk}) > 0.1$ is imposed to veto very close-by tracks associated to the ID lepton.

$\Delta d_0(\text{lep}, \text{trk})$ and $\Delta z_0(\text{lep}, \text{trk})$

The differences of impact parameters between the ID lepton and the lepton track $\Delta d_0(\text{lep}, \text{trk})$ and $\Delta z_0(\text{lep}, \text{trk})$ defined by

$$\Delta d_0(\text{lep}, \text{trk}) = |d_0(\text{lep}) - d_0(\text{trk})|,$$

$$\Delta z_0(\text{lep}, \text{trk}) = |z_0(\text{lep}) - z_0(\text{trk})|$$

are also used to preselect candidate tracks. The d_0 and z_0 of the lepton and the track should be close since they both come from the same Z^* decay. For the electron channel, $\Delta d_0(\text{lep}, \text{trk}) < 0.25$ mm and $\Delta z_0(\text{lep}, \text{trk}) < 0.30$ mm are required. For the muon channel, $\Delta d_0(\text{lep}, \text{trk}) < 0.10$ mm and $\Delta z_0(\text{lep}, \text{trk}) < 0.26$ mm are required.

6.3 Parameterized neural network for event selection

The event topology of signal events has large dependence on the mass splitting of the higgsinos, namely $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. For very small $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, the leptons emitted from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay have very low p_T , and the two $\tilde{\chi}_1^0$ tend to become more collimated, leading to higher E_T^{miss} values. In this case, variables such as $dR(\text{lep}, \text{trk})$ and $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$ have very small values. For larger $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, the leptons have higher p_T , leading to lower E_T^{miss} , and therefore, larger $dR(\text{lep}, \text{trk})$ and $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$.

To consider these dependencies and to classify signal and background events in a dynamic manner, *parameterized neural network* (pNN) [111] is introduced. Fig. 6.3 shows a schematic diagram of pNN. By choosing $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ as the physics parameter θ (hereinafter referred to as pNN- θ), it is possible to realize $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ -dependent event selection with a single network model. This also simplifies the training procedure, as pNN has the ability to smoothly interpolate between $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ used for training, thus giving the possibility to explore various mass splitting scenarios with limited number of training samples. This section describes the inputs, the model and its training, and the performance of the pNN designed for event selection.

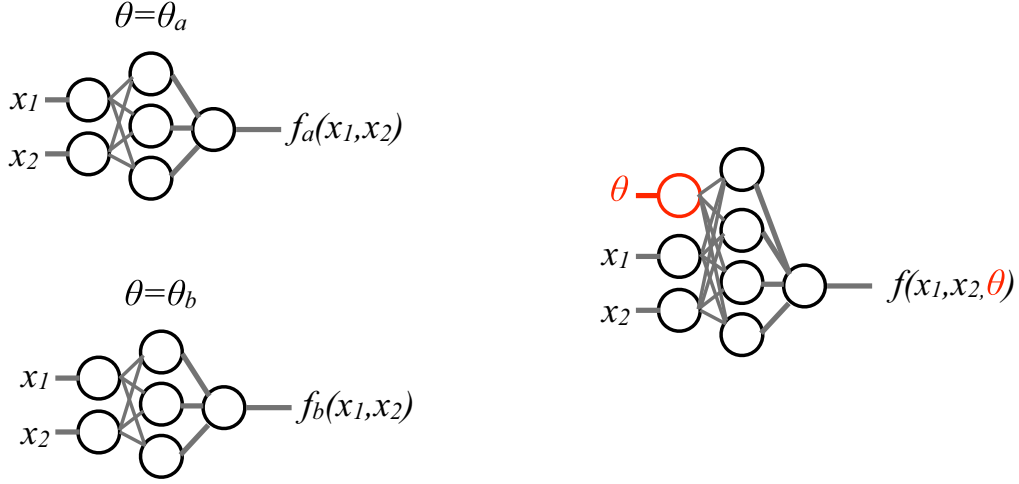


Figure 6.3: Schematic diagram of pNN [111]. In the case where input features x_1 and x_2 depend on the physics parameter θ , with conventional neural networks, a dedicated neural network for each θ value would be necessary to realize optimized performance (left). Instead with parameterized neural networks, only a single network is necessary to achieve the purpose, simply by using θ as one of the inputs to the network (right).

6.3.1 Input variables

The input variables of the pNN are summarized in Table 6.3. The same set of variables are used for both electron and muon channels, because they are expected to have the same event topology. However, a separate network is prepared for each channel, since the kinematic requirements of leptons and tracks differ as mentioned in Section 6.2.

Out of the 16 input variables (excluding pNN- θ), lepton p_T , track p_T , E_T^{miss} , leading jet p_T , $m(Z^*)$, $dR(\text{lep}, \text{trk})$, $H(\text{lep}, \text{trk})/E_T^{\text{miss}}$, $m_T(\text{lep}, E_T^{\text{miss}})$, $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$, and $\Delta\phi(j_1, Z^*)$ have significant dependencies on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, thus having high importance. Normalized distributions of these input variables are shown in Fig. 6.4 and Fig. 6.5 for the electron channel and the muon channel, respectively. The topology differences between signal and background events tend to become more significant for smaller $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$.

6.3.2 Model and training

Fig. 6.6 shows the overall structure of the pNN model developed for event selection. This model is used for both electron and muon channels. Based on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, which is the pNN- θ , and 16 kinematic variables, the algorithm outputs a signal event likeliness score (hereinafter referred to as pNN score) ranging from 0 to 1. All of the inputs are standardized following Eq. 5.1.

Since the kinematic requirements for leptons and tracks differ for the electron and muon channel, the training of pNN has been done separately for each channel using the same pNN model. To ensure enough statistics, higgsino production MC events have been used inclusively in terms of mass points and production channels as signal training samples. W +jets MC events have been used as background training samples. pNN- θ of background training samples are assigned randomly so that its distribution matches that of the signal training samples. All training samples are required to pass the event

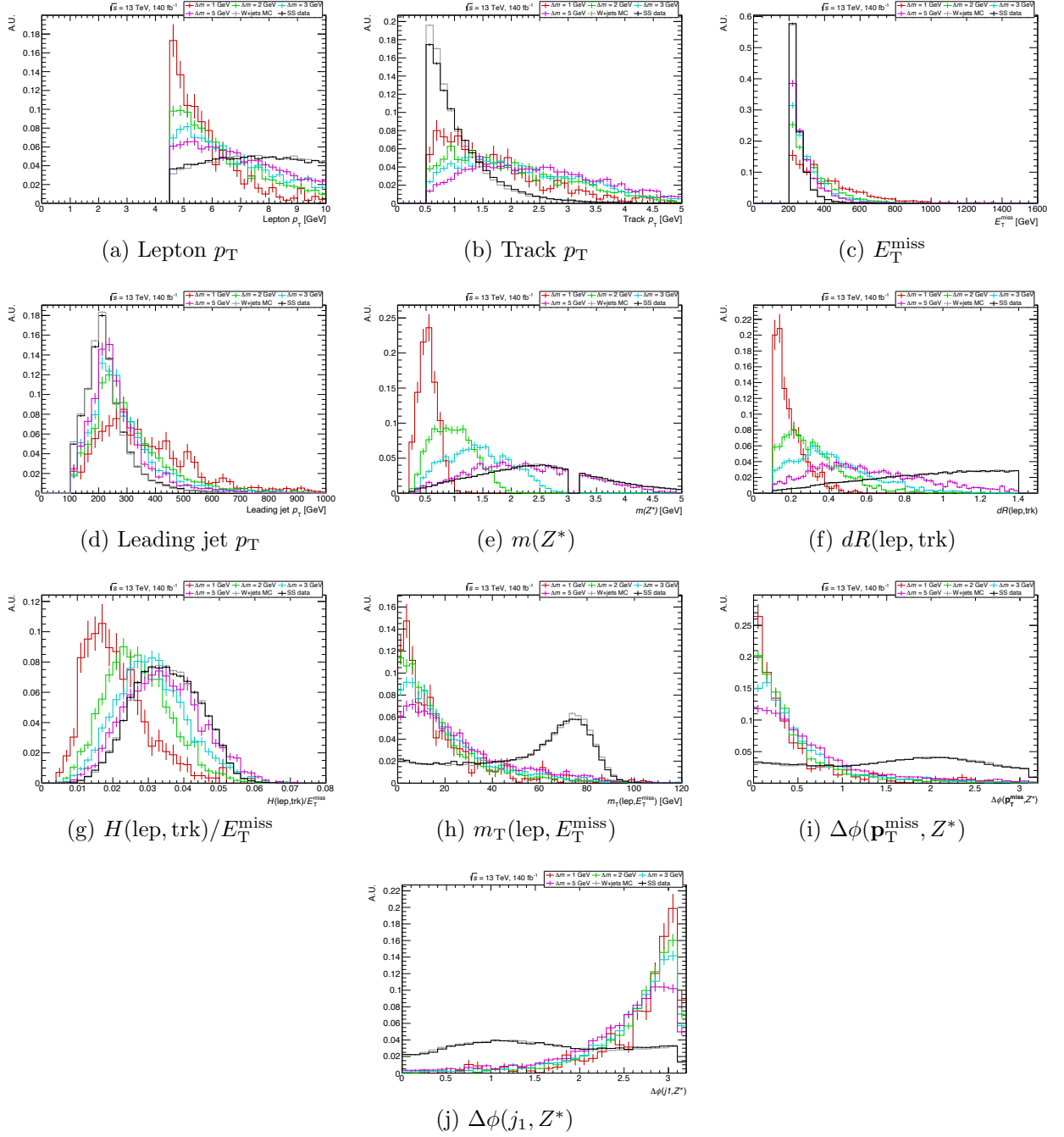


Figure 6.4: Normalized distributions of pNN input variables for electron channel. Signals with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 1, 2, 3, 5$ GeV, W +jets MC, and same-sign (SS) data are shown. SS data refers to actual data but with flipped charge requirements for the track; the track is required to have the same sign charge with the ID lepton. For signals, various $m(\tilde{\chi}_1^0)$ scenarios are plotted inclusively, ranging from 85 to 175 GeV. Out of the 16 input variables excluding pNN- θ , only variables with high importance are shown. Note that the selection criteria in Table 6.1 and Table 6.2 are applied.

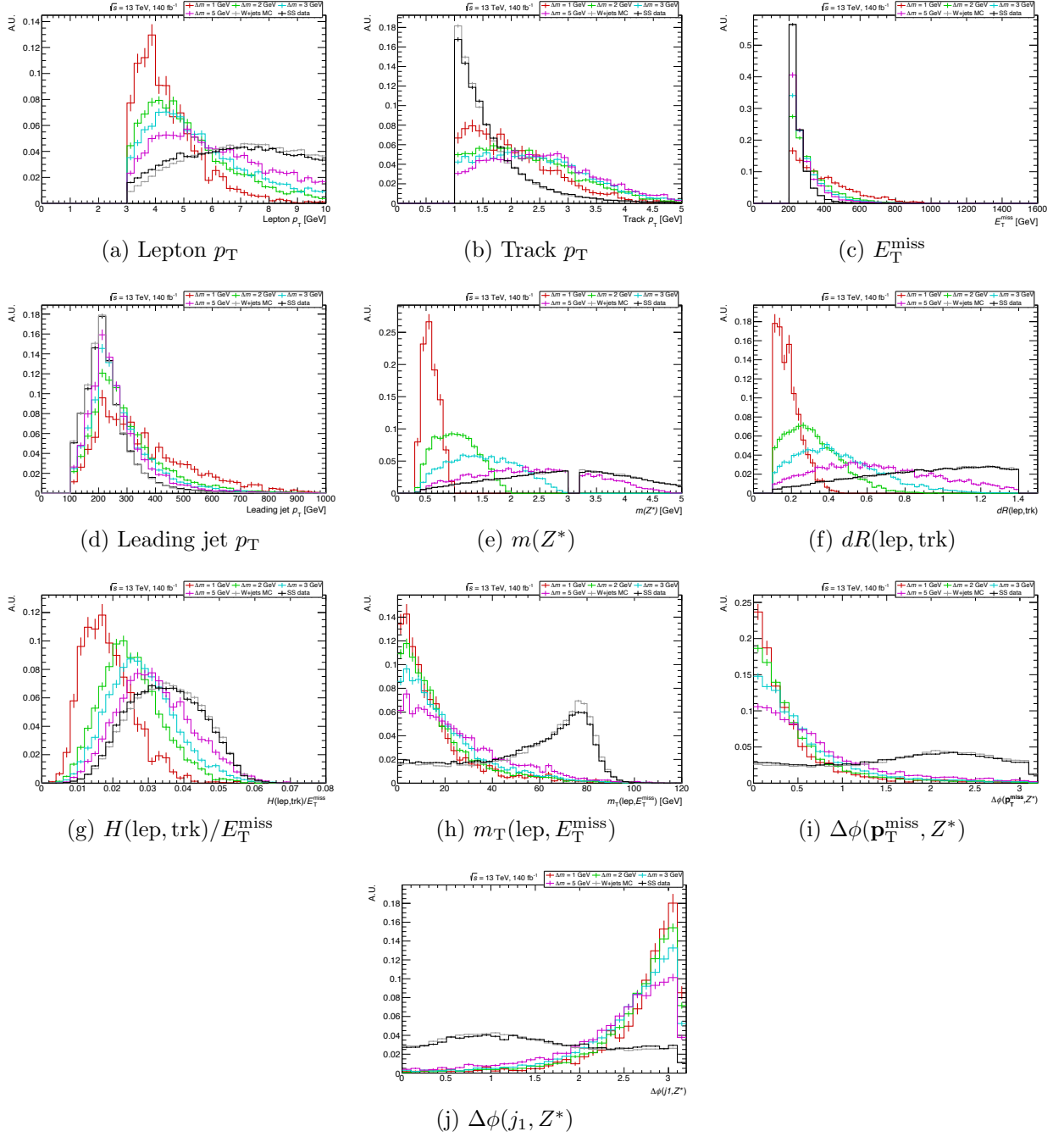


Figure 6.5: Normalized distributions of pNN input variables for muon channel. Signals with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 1, 2, 3, 5$ GeV, W +jets MC, and same-sign (SS) data are shown. SS data refers to actual data but with flipped charge requirements for the track; the track is required to have the same sign charge with the ID lepton. For signals, various $m(\tilde{\chi}_1^0)$ scenarios are plotted inclusively, ranging from 85 to 175 GeV. Out of the 16 input variables excluding pNN- θ , only variables with high importance are shown. Note that the selection criteria in Table 6.1 and Table 6.2 are applied.

Table 6.3: Summary of input variables of the pNN. The same set of variables are used for both electron and muon channels.

Input variable	Description
$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$	pNN- θ , mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$
Lepton p_T	Kinematics of ID lepton
Lepton η	
Lepton ϕ	
Track p_T	
Track η	Kinematics of track
Track ϕ	
E_T^{miss}	
$\phi(\mathbf{p}_T^{\text{miss}})$	Kinematics of missing energy
Leading jet p_T	
Leading jet ϕ	Kinematics of leading jet
$m(Z^*)$	
$dR(\text{lep}, \text{trk})$	Distance between the lepton and the track
$H(\text{lep}, \text{trk})/E_T^{\text{miss}}$	Ratio of scalar sum of lepton p_T and track p_T to E_T^{miss}
$m_T(\text{lep}, E_T^{\text{miss}})$	Transverse mass reconstructed from the lepton and E_T^{miss}
$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$	Angular difference between the missing momentum and reconstructed Z^*
$\Delta\phi(j_1, Z^*)$	Angular difference between the leading jet and reconstructed Z^*

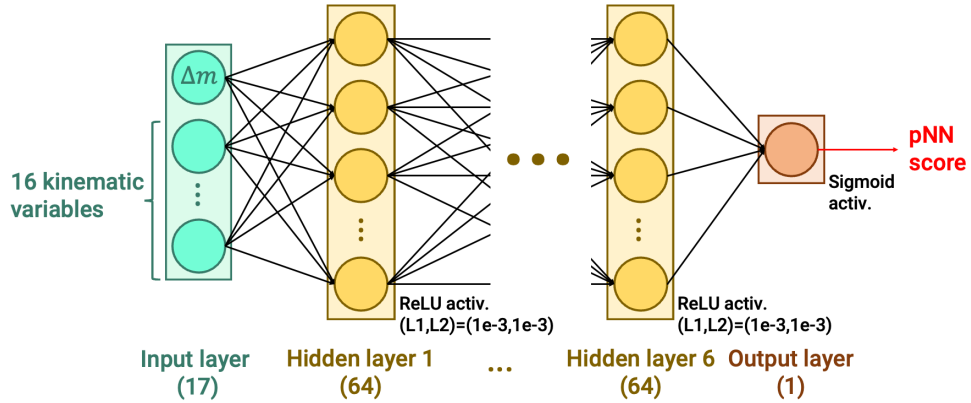


Figure 6.6: Overall structure of the pNN model used for event selection. $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ and 16 kinematic variables are used as inputs, and there are six hidden layers with 64 nodes each. The nodes are fully connected. L1 and L2 regularizations are applied to each layer to prevent overtraining. The output pNN score ranges from 0 to 1, with 1 meaning that the input event is signal event-like.

and track preselections described in Section 6.2. For the electron channel, about 22k signal events and 630k background events are used for the training, in which 20% were assigned as validation samples. For the muon channel, about 51k signal events and 380k background events are used for the training, in which 20% were assigned as validation samples. The training configurations of the pNN are summarized in Table 6.4, common to both channels.

Table 6.4: Summary of the training configurations of event selection pNN.

Hyperparameter	Value
Batch size	128
EarlyStopping	Enabled (Patience = 10)
Learning rate	0.0001
Loss type	Binary crossentropy
Optimizer	Adam

6.3.3 Performance

Fig. 6.7 and Fig. 6.8 show the training and testing pNN score distributions for the electron channel and the muon channel, respectively. Fig. 6.9 shows the ROC curves for each pNN- θ for each channel, derived by scanning the testing pNN score distributions. As expected from the distributions of the input variables shown in Fig. 6.4 and Fig. 6.5, the classification performance is higher for smaller pNN- θ values.

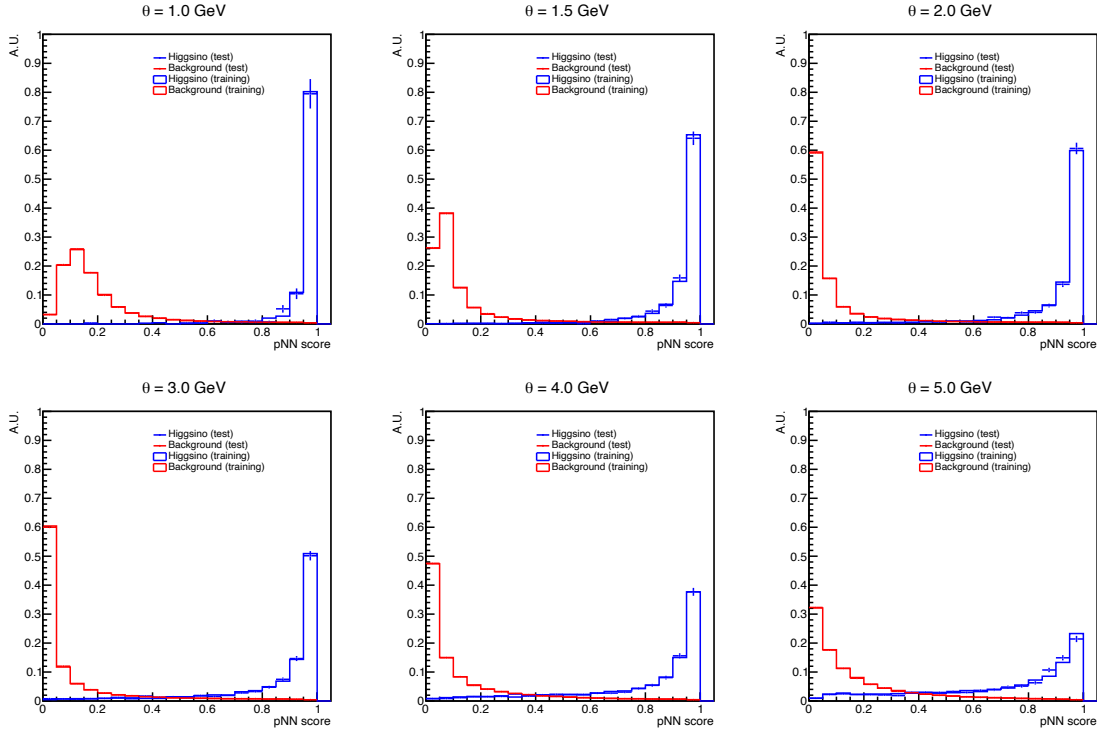


Figure 6.7: Electron channel pNN score distribution for each pNN- θ . The training and testing distributions agree well; no overtraining is observed.

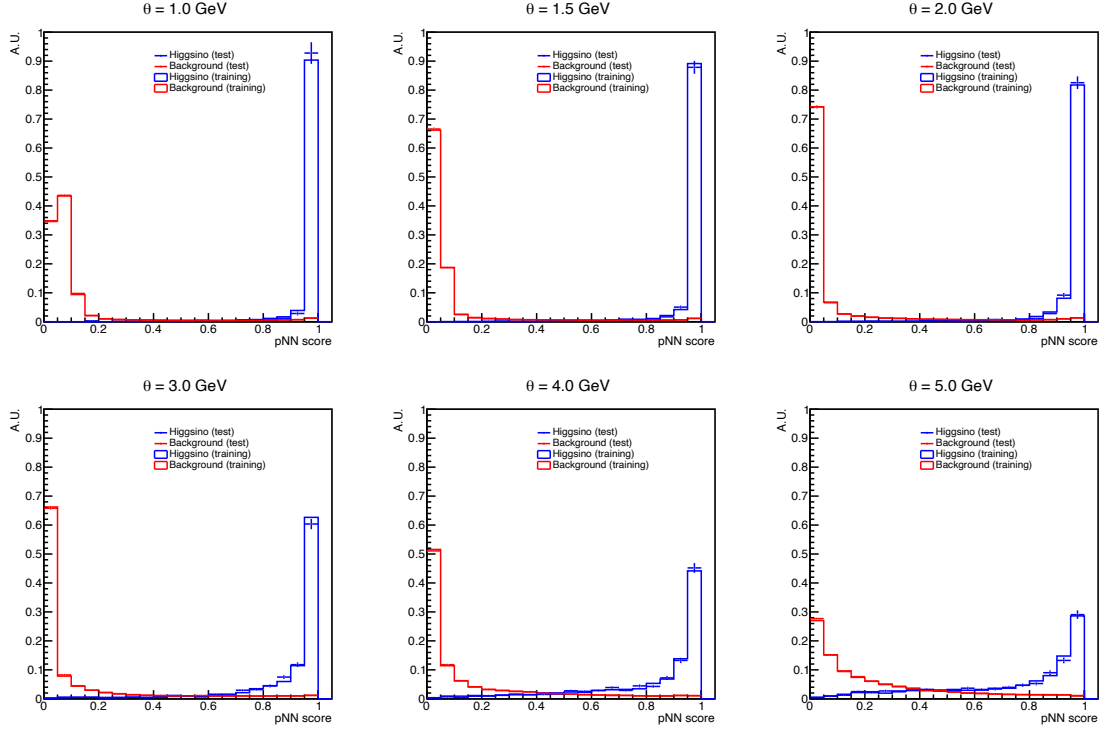


Figure 6.8: Muon channel pNN score distribution for each pNN- θ . The training and testing distributions agree well; no overtraining is observed.

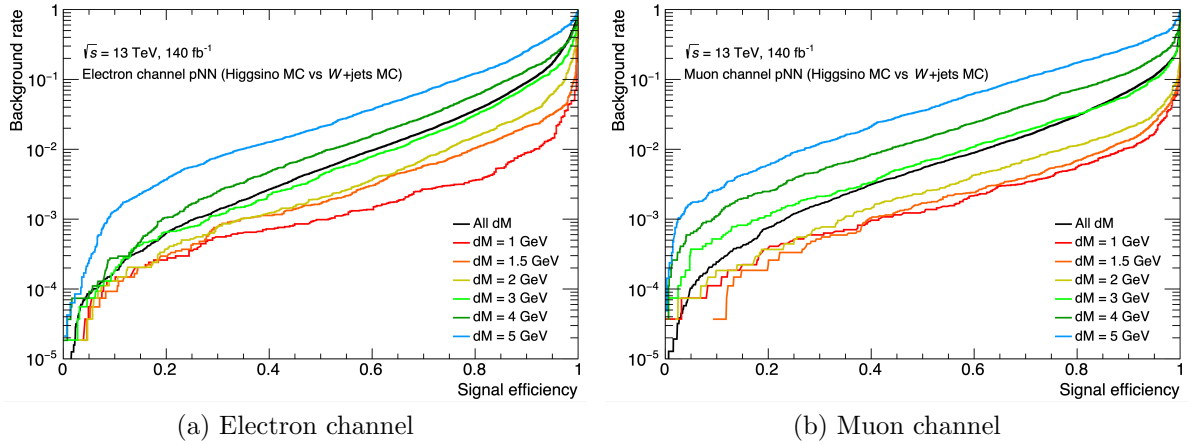


Figure 6.9: ROC curves of pNN for each pNN- θ . The performance is better for smaller $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ values for both channels.

6.3.4 Application

In the case where a simple neural network is used for a search analysis, the neural network model is trained and optimized for each mass point. On the other hand, pNN has a single model trained to perform for each of the mass points, but with additional degrees of freedom, which could be adjusted manually. In the analysis, the degree of freedom is the pNN- θ , corresponding to the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$.

The pNN in this search analysis is trained with pNN- $\theta = 1, 1.5, 2, 3, 4$ and 5 GeV. The same values are used for the search by fixing the pNN- θ to each value. Therefore, there are six models to choose from for each mass point. Straightforwardly, the best performing model for each mass point should be the one having the same pNN- θ , however, this might not always be the case due to fluctuations. Hence, the best performing pNN- θ is chosen for each mass point by comparing the final CL_s values obtained from statistical analysis described later in Section 9.

6.4 Signal Region definition

Fig. 6.10 shows the flow of this search analysis. Event and track preselection requirements defined in Section 6.2 are first applied. Next, a single track with the highest pNN score is selected for each event. This is performed by reconstructing the Z^* candidate and applying the pNN with each of the preselected tracks. After the track selection, cuts on $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$ and the pNN score are applied to select signal-like events. The regions that fail these requirements are used as Validation Regions (VRs) of the background estimation method. Finally, low- p_T lepton track ID is applied to the selected track with dedicated WPs. The regions passing the low- p_T lepton track ID requirement are used as Signal Regions (SRs). The definition of SRs is discussed in this section.

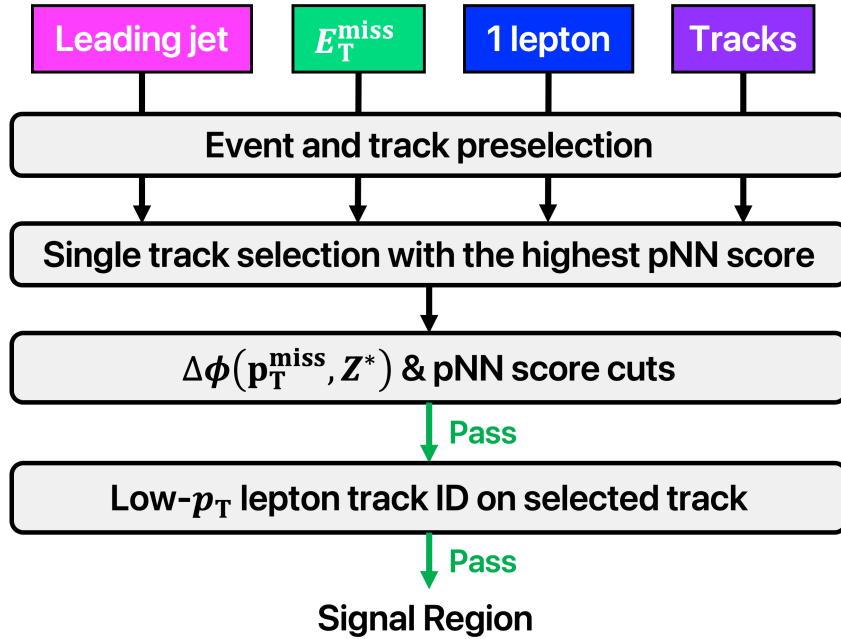


Figure 6.10: Diagram of the overall analysis flow. The basic flow is common to the electron and muon channels, while the detailed requirements slightly differ for each channel.

The general idea of SR definition is to maximize the sensitivity towards signals by choosing regions where the signal contribution is relatively high compared to SM background contributions. This is achieved by applying two independent selections on the main variables of the analysis: the pNN score and the low- p_T lepton track ID score. By first selecting events with high pNN scores, background events having non-signal-like event topology are vetoed. Then by selecting events having a track with high low- p_T lepton track ID WP score, significant background suppression is achieved by rejecting hadronic and fake tracks, which are the main background track components in the targeted regime.

Table 6.5 summarizes the selection criteria of SRs for the electron channel and the muon channel. The requirement on $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$ is imposed to keep the orthogonality with Validation Regions defined for the background estimation method and is common to both channels. The requirements on the pNN score and low- p_T lepton track ID WP score have been optimized to realize maximum sensitivity with expected background assuming 20% uncertainty.

Table 6.5: Summary of the selection criteria of SR.

Variable	Electron channel	Muon channel
$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$		< 1
pNN score		> 0.95
Low- p_T lepton track ID	LPET WP score > 0.8	LCaT muon WP score > 0.6

7. Methodology of Background Estimation

In this section, the main sources of background events are presented, followed by the details of the strategy of estimating the background contribution in the Signal Region.

7.1 Background components

All SM processes with a high- p_T jet and a boosted system with neutrinos in the final state could pass the leading jet and E_T^{miss} selection of this search. The requirements for the ID lepton, which the standard lepton identification is applied to, are relatively tight, hence the ID lepton is expected to be a real lepton in most cases. On the other hand, the requirements for the low- p_T lepton track, which the newly developed low- p_T lepton track identification method is applied to, are much looser; its main contribution is hadronic/fake tracks. Since the tracks are required to be associated with the hard-scatter vertex and have no surrounding activities, most of the background tracks are expected to be originating from underlying events. Some of these tracks could potentially imitate the signal lepton track originating from Z^* .

Considering that the target event topology requires a high- p_T hadronic jet, large missing momentum, and a single lepton, the most probable background process is W +jets, where the W decays leptonically. Fig. 7.1 shows the diagram of W +jets process. In this process, the true lepton originating from the W will likely be identified as the ID lepton, and the neutrino will likely result in high E_T^{miss} signature. As already mentioned, the hadronic/fake tracks would fake the low- p_T lepton track in this case. Moreover, there could also be small contributions from true leptonic tracks. Z +jets, diboson, and other processes which could possibly have two or more true leptons in their final states, could contribute as “true lepton” backgrounds. The dominant background with a “fake low- p_T lepton track” is estimated by a data-driven method described in Section 7.2, whereas the subdominant background with a “true low- p_T lepton track” is estimated directly from MC simulation as described in Section 7.3. A semi data-driven method is therefore used for the background estimation of the analysis.

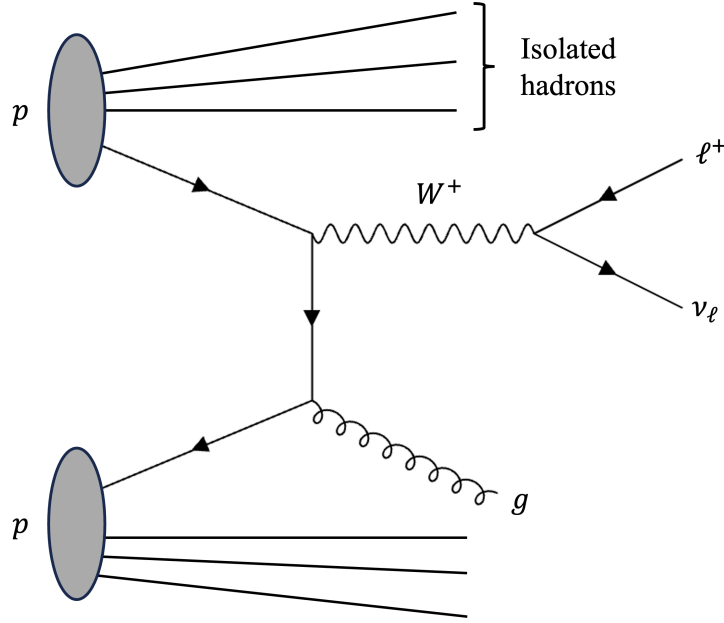


Figure 7.1: Diagram of W +jets process. This process is the main background of this search.

7.2 Data-driven estimation of 1L + fake lepton track background

A data-driven method has been adopted to estimate the dominant hadronic/fake track background in the SR due to the following reasons:

- The reliability of MC simulation modeling of low- p_T hadronic/fake tracks is not fully understood,
- Systematic uncertainties for the MC modeling of fake low- p_T lepton track would not have to be considered, allowing for a more accurate estimation.

The general idea of this method is to measure and apply the pass-to-fail ratios or the “transfer factors” of the low- p_T lepton track ID in certain Control Regions (CRs), having different kinematics compared to the SR. The validity of the method is verified in multiple Validation Regions (VRs). This transfer factor method is compatible with the analysis flow visualized in Fig. 6.10 and is common to both electron and muon channels.

Although the method mentioned above is expected to estimate nearly 90% of the total background in the SR, it has been observed in VRs that the above method does not fully consider relatively small contributions from true leptons to the low- p_T lepton track. These contributions are estimated using MC simulations as discussed later in Section 7.3. For the estimation of fake lepton track background, the contributions from “true leptons” are subtracted from data in each of the CRs to properly measure the hadronic/fake track transfer factors.

CR definitions and estimation procedures

Here, the definitions of the CRs used for measuring and applying the low- p_T lepton track ID transfer factors are described. The definitions are identical for both electron and muon channels.

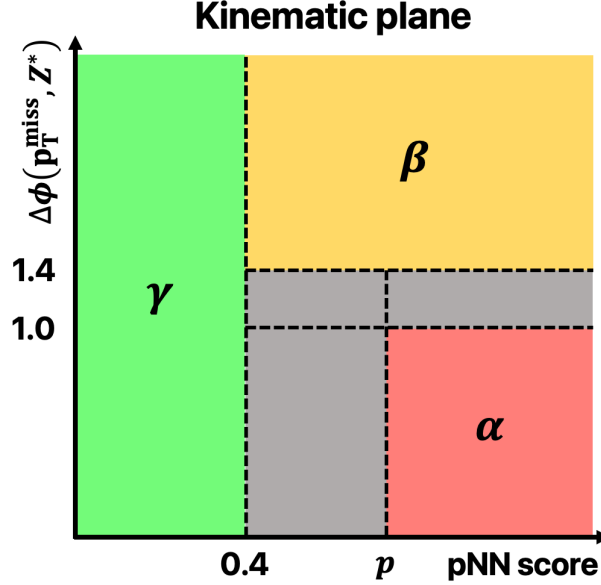


Figure 7.2: Kinematic plane diagram used for region definitions. In terms of kinematics, the SR, CRs, and VRs are defined by imposing cuts on the pNN score and $\Delta\phi(\mathbf{p}_T^{\text{miss}}, \mathbf{Z}^*)$.

Fig. 7.2 shows the kinematic plane used to define the SR, CRs, and VRs. The SR, which has already been defined in Section 6.4, is within the α -region, where pNN score threshold p is defined in Table 6.5 for each channel. It must be noted that the kinematic regions defined here do not consider the low- p_T lepton track ID requirements in Table 6.5; therefore, the SR is defined by the region passing the low- p_T lepton track ID WP within the α -region.

Since the low- p_T lepton track ID and the event selection pNN are defined independently of each other, the low pNN score region, dominated by SM background, is a valid region for measuring the transfer factors. In particular, the kinematic γ -region, with pNN scores lower than 0.4, is used. Within this γ -region, the region passing the low- p_T lepton track ID WP requirements (WP pass region) in Table 6.5 is defined as CR-A, and the region failing the WP requirements (WP fail region) is defined as CR-B. The transfer factors are then measured by taking the ratio of the number of events belonging to CR-A to that of CR-B. To consider the effects of indirect relations between the low- p_T lepton track ID and the pNN through the track kinematics, the transfer factors are measured separately for each of the track p_T bins listed in Table 7.1. This track p_T binned transfer factor method is capable of estimating the pNN score shape in the WP pass region.

The measured transfer factors are then applied to the WP fail region within the kinematic α -region, defined as CR-C. This method is expected to correctly estimate the pNN score shape in the SR, and its validity has been checked with MC simulated samples. Fig. 7.3 shows a schematic diagram of the background estimation method, summarizing the definition of each CR.

Table 7.1: List of track p_T bins used for low- p_T lepton track ID transfer factor measurement. The electron channel has an additional bin compared to the muon channel, since the target track p_T range is lower.

Track p_T bin name	Electron channel	Muon channel
Track p_T bin A	[0.5, 1.0] GeV	-
Track p_T bin B	[1.0, 1.5] GeV	
Track p_T bin C	[1.5, 2.0] GeV	
Track p_T bin D	[2.0, 3.0] GeV	
Track p_T bin E	[3.0, 5.0] GeV	

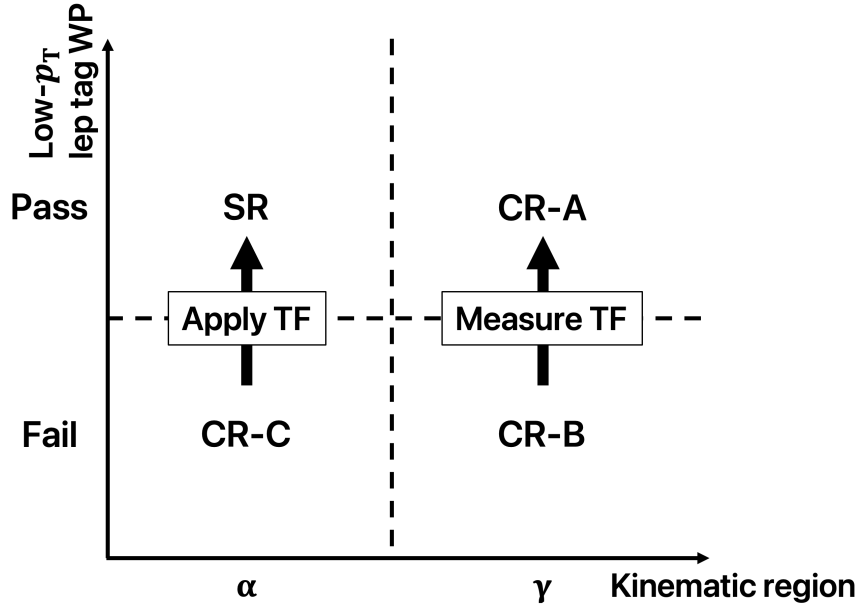


Figure 7.3: Schematic diagram of the background estimation method. CR-A and CR-B are used to measured the transfer factors (pass-to-fail ratio) of the low- p_T lepton track ID WP. The transfer factors are binned by the track p_T to correctly estimate the pNN score shape in the SR. The measured transfer factors are then applied to CR-C to estimate the background in the SR.

7.3 MC estimation of 1L + true lepton track background

As briefly mentioned in the previous section, the subdominant contribution of 1L + true lepton track background is estimated using MC simulation. These contributions are considered by adding them directly to the data-driven estimated fake lepton track contribution in the SRs and VRs. The considered background MC samples are listed in Table 3.3, and true lepton tracks are selected by matching with corresponding truth particles. Processes which have two or more prompt leptons, such as Z +jets and diboson production, tend to have small but non-negligible contributions. The effects of non-prompt leptons from processes such as dijet production and γ +jets have also been checked but were found to be negligible.

7.4 Validation strategy

The background estimation method described in Sections 7.2 and 7.3 must be validated by checking the agreement of estimated background and data in certain VRs. This is done in multiple VRs, having sufficiently low signal contamination. The VRs are used to evaluate the non-closure systematics of the background estimation method later described in Section 8.

Since the estimation method assumes that the transfer factors measured in the low pNN score region are also valid in the high pNN score region, this validity must be checked with a dedicated VR. This is done within the kinematic β -region in Fig. 7.2, defined by pNN score > 0.4 and $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*) > 1.4$. Although the SR is defined by $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*) < 1.0$, the cut threshold for the β -region has been raised to 1.4 to suppress signal contamination. Fig. 7.4 shows the schematic diagram of the validation using the kinematic β -region. By applying the measured transfer factors to CR-highLarge, which corresponds to the WP fail region within the β -region, the number of events in VR-highLarge, defined by WP pass region within the β -region, is estimated.

Additional VRs are considered to verify the validity of the background estimation method in the α -region. This is performed by flipping the charge or the flavor relations between the ID lepton and the low- p_T lepton track. For the SR shown in Fig. 7.3, the ID lepton and the low- p_T lepton track are required to have opposite signs (OS) and be of the same flavor (SF), namely, electrons for the electron channel and muons for the muon channel. For additional VRs, the ID lepton and the low- p_T lepton track are required to have the same sign (SS) or different flavors (DF), with other requirements set identically to those of the SR. For these two VRs and their corresponding CRs, the pNN score thresholds for α -regions are lowered to 0.4 to increase statistics.

For the same sign VR, defined as VR-SS, the transfer factors are measured and applied within the same sign region; therefore, additional CRs named CR-SS-A, CR-SS-B, and CR-SS-C are defined in correspondence with the three CRs shown in Fig. 7.3. Fig. 7.5 shows the schematic diagram of the validation using VR-SS. The estimated background in VR-SS is compared to data for validation.

For the different flavor VR, defined as VR-DF, the transfer factors are measured and applied within the different flavor region. For the electron channel, an ID muon and a low-

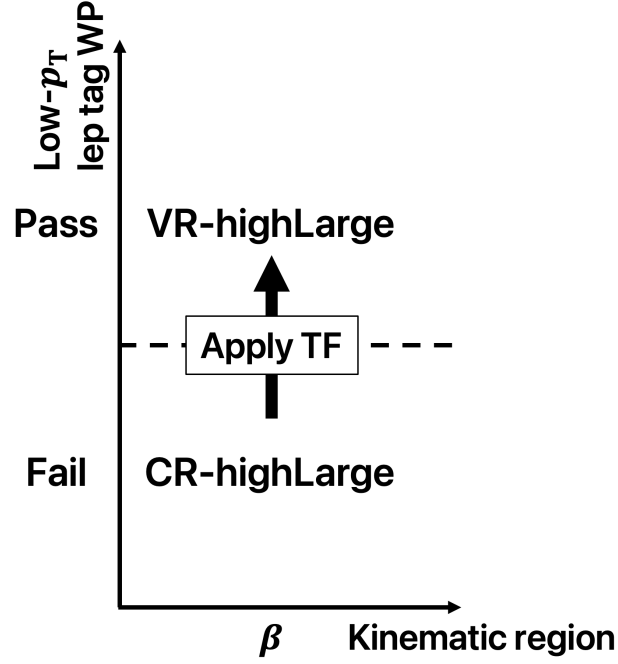


Figure 7.4: Schematic diagram of the background estimation validation in VR-highLarge. The transfer factors measured in the low p_{NN} score region are applied to CR-highLarge to estimate the number of events in VR-highLarge.

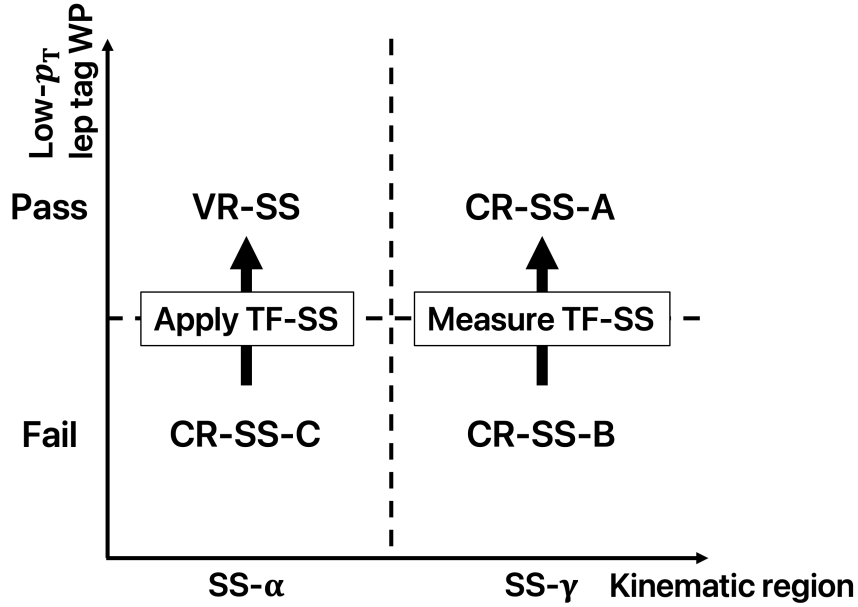


Figure 7.5: Schematic diagram of the background estimation validation in VR-SS. CR-SS-A and CR-SS-B are used to measure the same sign transfer factors (TF-SS) of the low- p_T lepton track ID WP. The transfer factors are binned by the track p_T using the same binning as the OS-SF regions. The measured transfer factors are then applied to CR-SS-C to estimate the background in VR-SS.

p_T electron track are considered to measure the transfer factors of LPET ID. For the muon channel, an ID electron and a low- p_T muon track are considered to measure the transfer factors of LCaT muon ID. Therefore, additional CRs named CR-DF-A, CR-DF-B, and CR-DF-C are defined in correspondence with the three CRs shown in Fig. 7.3. Fig. 7.6 shows the schematic diagram of the validation using VR-DF. The estimated background in VR-DF is compared to data for validation.

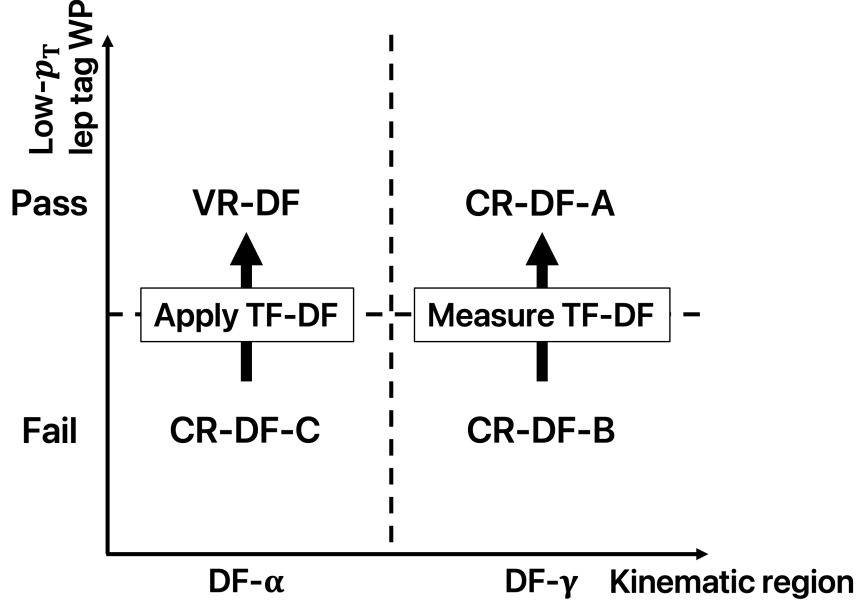


Figure 7.6: Schematic diagram of the background estimation validation in VR-DF. CR-DF-A and CR-DF-B are used to measured the different flavor transfer factors (TF-DF) of the low- p_T lepton track ID WP. The transfer factors are binned by the track p_T using the same binning as the OS-SF region. The measured transfer factors are then applied to CR-DF-C to estimate the background in VR-DF.

7.5 Summary of CR and VR definitions

In summary, there are three VRs and 10 CRs for each channel as listed in Table 7.2. Three CRs (CR-A/B/C) are necessary for estimating the SR background: two for TF measurement and one for TF application. The remaining seven CRs are dedicated to validation: one (CR-highLarge) for VR-highLarge, three (CR-A/B/C-SS) for VR-SS, and three (CR-A/B/C-DF) for VR-DF. It should be again noted that the contributions from true lepton tracks are subtracted from CRs before measuring the transfer factors and are added to SRs and VRs afterwards.

Table 7.2: List of CRs and VRs used in the analysis. The pNN score threshold p is the value used for the SR definition, listed on Table 6.5. Note that the pNN score thresholds for α -regions for SS-SF and OS-DF are lowered to 0.4 to increase statistics.

Region name	Sign	Flavor	pNN score	$\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$	WP	Description
CR-A	OS	SF	< 0.4	-	Pass	TF measurement numerator
CR-B	OS	SF	< 0.4	-	Fail	TF measurement denominator
CR-C	OS	SF	$> p$	< 1.0	Fail	TF application CR for SR
CR-highLarge	OS	SF	> 0.4	> 1.4	Fail	TF application CR for VR-highLarge
CR-A-SS	SS	SF	< 0.4	-	Pass	TF-SS measurement numerator
CR-B-SS	SS	SF	< 0.4	-	Fail	TF-SS measurement denominator
CR-C-SS	SS	SF	> 0.4	< 1.0	Fail	TF-SS application CR for VR-SS
CR-A-DF	OS	DF	< 0.4	-	Pass	TF-DF measurement numerator
CR-B-DF	OS	DF	< 0.4	-	Fail	TF-DF measurement denominator
CR-C-DF	OS	DF	> 0.4	< 1.0	Fail	TF-DF application CR for VR-DF
VR-highLarge	OS	SF	> 0.4	> 1.4	Pass	VR within OS-SF with large $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$
VR-SS	SS	SF	> 0.4	< 1.0	Pass	VR with SS-SF
VR-DF	OS	DF	> 0.4	< 1.0	Pass	VR with OS-DF

7.6 Estimation results in the Signal Region

By adding the data-driven estimated fake lepton track contribution and MC estimated true lepton track contribution, the total SM background in the SR is estimated for the electron and muon channels for each pNN- θ , as mentioned in Section 6.3.4. This is done by applying the systematic uncertainties later described in Section 8 and using the statistical fit framework described in Section 9. Table 7.3 and Table 7.4 summarize the estimated event yields in the SR for the electron channel and the muon channel, respectively.

Table 7.3: Expected event yields in the SR for the electron channel, for each pNN- θ . “Others” includes true e track contributions from top, dijet, and γ +jets processes.

pNN- θ [GeV]	1	1.5	2	3	4	5
Total fitted SM events	1.43 ± 0.37	2.44 ± 0.56	4.41 ± 0.92	8.44 ± 1.78	9.88 ± 2.36	5.76 ± 1.75
Fake e track	1.10 ± 0.28	1.93 ± 0.48	3.65 ± 0.83	7.64 ± 1.76	8.61 ± 2.24	4.74 ± 1.66
Diboson true e track	0.22 ± 0.18	0.42 ± 0.28	0.65 ± 0.42	0.67 ± 0.43	0.78 ± 0.53	0.65 ± 0.44
W +jets true e track	$0.10^{+0.14}_{-0.10}$	$0.10^{+0.13}_{-0.10}$	$0.10^{+0.13}_{-0.10}$	$0.10^{+0.13}_{-0.10}$	$0.41^{+0.43}_{-0.41}$	$0.12^{+0.14}_{-0.12}$
Z +jets true e track	0.00 ± 0.00	0.00 ± 0.00	$0.00^{+0.01}_{-0.00}$	0.02 ± 0.02	0.09 ± 0.07	0.25 ± 0.20
Others	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Table 7.4: Expected event yields in the SR for the muon channel, for each pNN- θ . “Others” includes true μ track contributions from top, dijet, and γ +jets processes.

pNN- θ [GeV]	1	1.5	2	3	4	5
Total fitted SM events	6.54 ± 2.39	12.06 ± 4.44	17.06 ± 6.37	19.46 ± 7.20	12.68 ± 4.65	7.91 ± 3.25
Fake μ track	5.74 ± 2.34	10.80 ± 4.39	15.59 ± 6.33	17.47 ± 7.14	10.91 ± 4.60	6.38 ± 3.14
Diboson true μ track	0.79 ± 0.53	1.25 ± 0.78	1.33 ± 0.82	1.73 ± 1.03	1.37 ± 0.82	1.07 ± 0.65
W +jets true μ track	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	$0.00^{+0.01}_{-0.00}$	$0.00^{+0.01}_{-0.00}$	0.00 ± 0.00
Z +jets true μ track	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.12	0.26 ± 0.19	0.40 ± 0.26	0.46 ± 0.30
Others	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

8. Systematic Uncertainties

This section describes the systematic uncertainties considered in this search: experimental uncertainties, theoretical uncertainties, and analysis specific uncertainties. As the dominant background is the fake lepton track contribution estimated by the data-driven method, the non-closure uncertainty on that component is the most dominant source of the systematic uncertainty. Although contributions of background MC samples are relatively small and their systematic uncertainties should have little impact on the results, they have been evaluated to a certain extent.

8.1 Experimental uncertainties

Experimental uncertainties are considered for the MC samples to account for the mis-modeling in detector responses and imperfections in calibrations. The considered experimental uncertainties are described below. Experimental uncertainties for the signal MC samples have been implemented straightforwardly by handling each of the uncertainties as separate nuisance parameters in the statistical analysis framework later described in Section 9. On the other hand, for background MC samples used for estimating the true lepton contribution, the experimental uncertainties have been handled as a flat 50% envelope systematic of all uncertainties described below and implemented to the statistical framework as a single nuisance parameter. This is to prevent fit instabilities in the framework, caused by low MC statistics. As the true lepton track contribution accounts for only about 10% of the SR background, its uncertainties are of second order and have minimal impact on the total uncertainty.

Electrons

- Energy resolution: up/down variations in the resolution of the electron energy.
- Energy scale: up/down variations in the scale of the electron energy.
- Reconstruction efficiency: up/down variations in the error of the electron reconstruction scale factors.
- Identification efficiency: up/down variations in the error of the electron identification working-point scale factors.
- Isolation efficiency: up/down variations in the error of the electron isolation working-point scale factors.

Muons

- Inner Detector smearing: up/down variations in the smearing of the muon tracks in the Inner Detector.
- Muon spectrometer smearing: up/down variations in the smearing of the muon tracks in the muon spectrometers.
- Momentum scale: up/down variations in the muon momentum scale.
- Sagitta resolution: up/down charge-dependent variations in the scale of the momentum and its statistical error associated to the charge-dependent corrections.
- Reconstruction efficiency: up/down variations in the statistical and systematic errors on the muon reconstruction scale factors.
- Isolation efficiency: up/down variations in statistical and systematic errors on the muon isolation working-point scale factors.
- Track-to-vertex association (TTVA) efficiency: up/down variations in statistical and systematic errors on the muon TTVA scale factors.

Jets

- Jet energy resolution: up/down variations in the smearing of the MC jets to the data to correct the MC resolution. These uncertainties are evaluated from dijet events and zero bias data using random cones.
- Jet energy scale: up/down variations in the scale of the jet momentum. These uncertainties are derived from the dijet eta-intercalibration across eta, $Z(\rightarrow ee, \mu\mu)+\text{jets}$, $\gamma+\text{jets}$ and multijet balance, and the propagation of single particles in high- p_T regimes.
- Jet vertex tagger: up/down variations accounting for the residual contamination from pileup jets in the central region.
- Flavor tagging efficiency: up/down variations in the error on the scale factors used to correct the simulation-over-data flavor tagging rate.

Missing transverse momentum

- Soft term resolution: one-sided variations of the E_T^{miss} track soft term resolution, parallel and perpendicular to the hard term.
- Soft term scale: up/down variations in the E_T^{miss} track soft term scale, obtained by scaling the soft term magnitude in the direction of p_T^{hard} .

Others

- Pileup: up/down variations of the pileup weight used to reweight nominal MC predictions to reproduce the correct distribution of the number of pp collisions per bunch crossing in data.
- Track impact parameter resolution: one-sided variations on the transverse and longitudinal impact parameter resolutions to account for any differences with respect to data. These uncertainties are obtained by replacing the nominal impact parameter with a random value taken from a Gaussian distribution, whose central value is the original MC impact parameter and whose sigma is taken from dedicated smearing maps from studies on MC/data resolution differences.

8.2 Theoretical uncertainties

Theoretical uncertainties for signal and background MC samples have been evaluated to consider generator-level modeling uncertainties. Note that for the background MC samples, all theoretical uncertainties have been considered only for diboson and V +jets samples, which are the dominant components of the true lepton track contribution. Uncertainties of other background processes have negligible impact and are hence not considered.

The following variations of QCD renormalization and factorization scales and parton distribution functions (PDFs) have been taken into account for both signal and background MC samples. These uncertainties are combined by taking their quadratic sum.

QCD renormalization and factorization scales

Renormalization and factorization scales (μ_R and μ_F) are used to estimate the uncertainties originating from truncated higher orders in the perturbative expansion of the partonic cross-section corrections. The uncertainties are estimated by varying μ_R and μ_F by a factor of two resulting in 7-point variations of $\{\mu_R, \mu_F\} = \{0.5, 0.5\}, \{1.0, 0.5\}, \{0.5, 1.0\}, \{1.0, 1.0\}, \{2.0, 1.0\}, \{1.0, 2.0\}, \{2.0, 2.0\}$. 3-point variations of $\{\mu_R, \mu_F\} = \{0.5, 0.5\}, \{1.0, 1.0\}, \{2.0, 2.0\}$ are used when the 7-point variations are unavailable at generator-level. The envelope of the 7-point (3-point) variations are taken as the overall uncertainty.

Parton Distribution Function (PDF)

PDFs at a given scale (Q) are determined by fitting a given functional form to data. The PDF at different energy scales in the MC generator is estimated by DGLAP equations [168–170]. Therefore, experimental uncertainties in the used dataset and uncertainty on the functional form for PDF fits are sources of uncertainties. Truncated higher order calculations of DGLAP equations could also be sources of uncertainties, however, they are considered by varying the renormalization and factorization scales as mentioned above.

Additionally, the following uncertainties are considered, depending on the signal and background processes.

Cross section uncertainty (for signal MC only)

The theoretical uncertainty on the cross section for signal MC is considered. Similar to the nominal cross section value, its uncertainty is also evaluated to NLO+NLL accuracy using RESUMMINO [130–135]. The relative uncertainty is less than 5% for all mass points.

Strong coupling constant (α_S) (for background MC only)

α_S is determined experimentally and quoted at the Z mass scale ($Q = m_Z$). α_S at different energy scales in the MC generators are predicted by renormalization group equations (RGEs), although the calculations are truncated at a given order. Therefore, experimental errors of α_S and missing higher order calculations of RGEs need to be accounted as uncertainties of α_S . PDF sets with different α_S values are used to estimate the uncertainties.

8.3 Analysis specific uncertainties

Additional uncertainties considered for this analysis are described below.

Low- p_T lepton track ID scale factor uncertainty

As described in Sections 5.1 and 5.2, low- p_T lepton track ID scale factors are applied to MC samples to consider the behavior differences between data and MC measured by the calibration. Up/down variations are applied by accounting for the uncertainties originating from the calibration, which primarily depends on the statistical uncertainties of the calibration data and the parametrization by track p_T . Uncertainties depending on track η and other parameters have been omitted for simplicity, because the impact of this scale factor uncertainty on the total background estimation is small, as this uncertainty is only applied to the subdominant true lepton track background component.

Non-closure uncertainty for background estimation

The non-closure of the background estimation method is expected to originate mainly from the uncertainties in the extrapolation of pNN scores using track p_T binned transfer factors, as the transfer factors could have dependencies on other variables. These uncertainties are evaluated by comparing the data and estimation in VRs and are applied as flat systematic uncertainties to the fake lepton track components in the SR. As a result of the evaluation, 15% and 40% flat systematics are applied to electron and muon channels, respectively.

CR statistical uncertainty

The statistical uncertainties of data in the CRs used for estimating the fake lepton background in the SR also have some impact. These have been considered as normalization factor and transfer factor uncertainties in the statistical analysis framework, later described in Section 9.

MC statistical uncertainty

The statistical uncertainties of the signal and background MC samples have been considered in all regions. The impact of the statistical uncertainties of the background MC samples is minimal, since the CRs are dominated by fake lepton contribution, and only a fraction of events are truly leptonic in the SR.

8.4 Impact on background estimation

Tables 8.1 and 8.2 show the impact of the systematic uncertainties on the estimated background for the electron channel and muon channel, respectively. The numbers have been obtained by performing statistical fits explained later in Section 9. Since the behavior is similar for all pNN- θ configurations, numbers for pNN- $\theta = 2$ GeV are shown as typical examples. For both channels, the non-closure uncertainty on the fake lepton track background is the most dominant. Other uncertainties on the fake lepton background, such as the transfer factor and normalization factor uncertainties, have non-negligible effects. On the other hand, as the contribution from true lepton track component is small, corresponding uncertainties such as the 50% envelope experimental uncertainty, MC statistical uncertainty, and the low- p_T lepton track ID scale factor uncertainty, have relatively small impact on the estimated background.

Table 8.1: Breakdown of the dominant systematic uncertainties on estimated background in SR for the electron channel for $p_{\text{NN}}\text{-}\theta = 2$ GeV. The percentages show the size of the uncertainty relative to the total expected background. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

Uncertainty of channel	SR-1e1T
Total background expectation	4.41
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.10
Total background systematic	± 0.92 [20.88%]
$\alpha_{\text{FakeBG_NonClosure_flatSys15}}$	± 0.55 [12.4%]
TF_TrackPtBinE_1e1T	± 0.47 [10.7%]
$\alpha_{\text{TrueBG_Experimental_flatSys50}}$	± 0.38 [8.6%]
mu_CR_C_TrackPtBinE_1e1T	± 0.32 [7.2%]
$\alpha_{\text{diboson_TheoryUnc}}$	± 0.22 [4.9%]
TF_TrackPtBinD_1e1T	± 0.21 [4.9%]
MC_stat_SR_1e1T	± 0.18 [4.2%]
$\alpha_{\text{Wjets_TheoryUnc}}$	± 0.12 [2.7%]
TF_TrackPtBinC_1e1T	± 0.10 [2.2%]
mu_CR_C_TrackPtBinD_1e1T	± 0.08 [1.8%]
TF_TrackPtBinB_1e1T	± 0.04 [0.88%]
$\alpha_{\text{LowPtLepTag}}$	± 0.04 [0.83%]
mu_CR_C_TrackPtBinC_1e1T	± 0.03 [0.61%]
mu_CR_C_TrackPtBinB_1e1T	± 0.01 [0.15%]
$\alpha_{\text{Zjets_TheoryUnc}}$	± 0.01 [0.13%]

Table 8.2: Breakdown of the dominant systematic uncertainties on estimated background in SR for the muon channel for $p_{\text{NN}}\text{-}\theta = 2$ GeV. The percentages show the size of the uncertainty relative to the total expected background. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

Uncertainty of channel	SR-1mu1T
Total background expectation	17.06
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 4.13
Total background systematic	± 6.37 [37.37%]
$\alpha_{\text{FakeBG_NonClosure_flatSys40}}$	± 6.23 [36.6%]
$\alpha_{\text{TrueBG_Experimental_flatSys50}}$	± 0.73 [4.3%]
TF_TrackPtBinC_1mu1T	± 0.58 [3.4%]
TF_TrackPtBinD_1mu1T	± 0.53 [3.1%]
TF_TrackPtBinE_1mu1T	± 0.52 [3.0%]
$\alpha_{\text{diboson_TheoryUnc}}$	± 0.41 [2.4%]
mu_CR_C_TrackPtBinC_1mu1T	± 0.37 [2.2%]
mu_CR_C_TrackPtBinD_1mu1T	± 0.30 [1.8%]
MC_stat_SR_1mu1T	± 0.27 [1.6%]
mu_CR_C_TrackPtBinE_1mu1T	± 0.23 [1.3%]
TF_TrackPtBinB_1mu1T	± 0.15 [0.87%]
$\alpha_{\text{Zjets_TheoryUnc}}$	± 0.09 [0.56%]
mu_CR_C_TrackPtBinB_1mu1T	± 0.05 [0.31%]
$\alpha_{\text{LowPtLepTag}}$	± 0.03 [0.19%]

9. Statistical Analysis

Statistical fits have been performed to estimate the number of events in the SRs and test its compatibility under various hypotheses. This has been done with a profile likelihood ratio approach using the `HistFitter` package [171]. This chapter describes the definition of the likelihood function and the methodology of hypothesis testing.

9.1 Likelihood function

The likelihood L of the electron or muon channel analysis is defined as the product of Poisson distributions of the number of events in the SR and CRs and the Gaussian probability densities of the systematic uncertainties:

$$L(\mathbf{n}|\mu_{\text{sig}}, \mathbf{s}, \mathbf{b}, \boldsymbol{\theta}) = P_{\text{SR}} \times P_{\text{CR-A}} \times P_{\text{CR-B}} \times P_{\text{CR-C}} \times C_{\text{syst}}, \quad (9.1)$$

where P_i is the Poisson measurement in region i , and C_{syst} is the product of Gaussian probability distributions of all considered systematic uncertainties. Poisson measurement P_i is represented by the observed number of events n_i and the expected number of λ_i in region i :

$$P_i = P(n_i|\lambda_i) = \frac{\lambda_i^{n_i}}{n_i!} e^{-\lambda_i}, \quad (9.2)$$

where the expected number of events λ_i is expressed as

$$\lambda_i(\mu_{\text{sig}}, s_i, \mathbf{b}, \boldsymbol{\theta}) = \mu_{\text{sig}} \cdot s_i(\boldsymbol{\theta}) + \sum_{\alpha \in \text{FakeLep}} b_{i,\alpha}(\boldsymbol{\theta}) + \sum_{\beta \in \text{TrueLep}} b_{i,\beta}(\boldsymbol{\theta}). \quad (9.3)$$

Each of the parameters in Eq. (9.3) are defined as below:

- μ_{sig} is the normalization factor of the signal process and is referred to as the signal strength.
- s_i is the expected number of signal events in region i , obtained from MC simulation.
- α represents the type of fake lepton background. As the fake lepton background is estimated with binning of track p_T as mentioned in Section 7.2, the summation runs over the track p_T bins listed in Table 7.1.
- $b_{i,\alpha}$ is the expected number of fake lepton background events, estimated by the data-driven method explained in Section 7.2. The data-driven estimation is performed by a simultaneous fit within the statistical fit framework.

- β represents the physics process of true lepton background MC.
- $b_{i,\beta}$ is the expected number of true lepton background events in region i for physics process β , obtained from MC simulation.
- θ represents the set of nuisance parameters, in particular, all of the considered systematic uncertainties mentioned in Section 8.

The systematic uncertainty factor C_{syst} is written as

$$C_{\text{syst}} = \prod_{j \in S} G(\theta_j), \quad (9.4)$$

where S is the set of all considered systematic uncertainties, and $G(\theta_j)$ is the standard Gaussian distribution of the systematic uncertainty θ_j . As the mean of the distribution is fixed to 0, $\theta = \pm 1$ corresponds to $\pm 1\sigma$ variations. Hereinafter, the likelihood will be denoted as $L(\mu_{\text{sig}}, \theta)$, as the number of signal and background events are functions of θ .

9.2 Hypothesis testing

For testing a certain hypothesized value of μ_{sig} , the following profile likelihood ratio (PLR) is considered [172]:

$$\text{PLR}(\mu_{\text{sig}}) = \frac{L(\mu_{\text{sig}}, \hat{\theta})}{L(\hat{\mu}_{\text{sig}}, \hat{\theta})}, \quad (9.5)$$

where $\hat{\mu}_{\text{sig}}$ and $\hat{\theta}$ maximize the likelihood function, and $\hat{\theta}$ maximize the likelihood function for a specific, fixed value of μ_{sig} .

Moreover, in the case where $\mu_{\text{sig}} \geq 0$, the test statistic $q_{\mu_{\text{sig}}}$ is defined as

$$\begin{aligned} q_{\mu_{\text{sig}}} &= -2 \ln (\text{PLR}(\mu_{\text{sig}})) \\ &= \begin{cases} -2 \ln \frac{L(\mu_{\text{sig}}, \hat{\theta})}{L(\hat{\mu}_{\text{sig}}, \hat{\theta})} & (\mu_{\text{sig}} \geq \hat{\mu}_{\text{sig}}) \\ 0 & (0 \leq \mu_{\text{sig}} < \hat{\mu}_{\text{sig}}). \end{cases} \end{aligned} \quad (9.6)$$

The p -value is then defined to quantify the level of agreement between the observed data and hypothesized μ_{sig} :

$$p_{\mu_{\text{sig}}} = \int_{q_{\mu_{\text{sig}}, \text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}}) dq_{\mu_{\text{sig}}}, \quad (9.7)$$

where $q_{\mu_{\text{sig}}, \text{obs}}$ is the observed value of $q_{\mu_{\text{sig}}}$. $f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}})$ is the probability density function of $q_{\mu_{\text{sig}}}$ assuming the signal strength of μ_{sig} , approximated as

$$f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}}) = \frac{1}{2\sqrt{q_{\mu_{\text{sig}}}}} \frac{1}{\sqrt{2\pi}} \left[\exp \left\{ -\frac{1}{2} \left(\sqrt{q_{\mu_{\text{sig}}}} + X \right)^2 \right\} + \exp \left\{ -\frac{1}{2} \left(\sqrt{q_{\mu_{\text{sig}}}} - X \right)^2 \right\} \right], \quad (9.8)$$

where X is defined to be

$$X = \frac{\mu_{\text{sig}} - \hat{\mu}_{\text{sig}}}{\sigma}, \quad (9.9)$$

using the standard deviation σ of $\hat{\mu}_{\text{sig}}$. In the case of signal-plus-background hypothesis and background-only hypothesis, the probability density function of the test statistic is given by $f(q_{\mu_{\text{sig}}}|\mu_{\text{sig}} = 1)$ and $f(q_{\mu_{\text{sig}}}|\mu_{\text{sig}} = 0)$, respectively.

For the analysis of this search, background-only hypothesis with $\mu_{\text{sig}} = 0$ is first considered to predict the number of background events in the SR for both electron and muon channels. If there is no significant excess of observed data compared to the prediction, model-dependent and model-independent fits are performed.

The model-dependent fit aims to quantify the exclusion of a certain model. This is done using the CL_s method [173]. In particular, CL_{s+b} , CL_b , and CL_s are defined as below:

$$CL_{s+b} = \int_{q_{\mu_{\text{sig}},\text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}}|\mu_{\text{sig}} = 1) dq_{\mu_{\text{sig}}} \equiv p_1, \quad (9.10)$$

$$CL_b = \int_{q_{\mu_{\text{sig}},\text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}}|\mu_{\text{sig}} = 0) dq_{\mu_{\text{sig}}} \equiv p_0, \quad (9.11)$$

$$CL_s \equiv \frac{p_0}{p_1}. \quad (9.12)$$

In this method, the signal hypothesis is considered to be excluded at 95% confidence level if $CL_s < 0.05$. This is the standard criterion for setting exclusion limits in the ATLAS experiment and is used in this analysis.

The model-independent fit aims to set upper limits on the number of events coming from physics beyond the SM. This is performed by scanning over the signal strength and calculating the p -value with Eq. (9.7) to find the number of expected and observed signal events for p -value at 0.05, denoted by S_{exp}^{95} and S_{obs}^{95} , respectively. The observed upper limit on the visible cross-section can also be calculated by

$$\langle \epsilon \sigma_{\text{obs}}^{95} \rangle = \frac{S_{\text{obs}}^{95}}{\int L dt}, \quad (9.13)$$

where the integrated luminosity $\int L dt$ for this search is 140 fb^{-1} .

9.3 Fit configuration

All of the systematic uncertainties described in Section 8 are implemented in the statistical fit framework as nuisance parameters. To speed up the fitting procedure, nuisance parameters are pruned when their deviation from the nominal value is less than 1%.

Simultaneous fit for data-driven estimation of fake lepton tracks

The dominant fake lepton track background is estimated using a data-driven method by measuring and applying transfer factors in dedicated CRs, as described in Section 7.2. Separate CRs are prepared for each track p_T bin shown in Table 7.1 to perform the track p_T binned transfer factor method. The SRs and VRs are prepared as track p_T inclusive regions; the track p_T binned estimations are summed in these regions. All of the procedures are implemented in the statistical fit framework, and the transfer factors and the expected number of fake lepton background are obtained by the simultaneous fit.

The transfer factor method is performed by first injecting *dummy* events into each CR and normalizing its number to the number of events in data subtracted by the true lepton contribution estimated by MC. Therefore, the normalization factor μ_{CR} is calculated by

$$\mu_{\text{CR}} \cdot n_{\text{dummy}} = n_{\text{data}} - n_{\text{trueLep}}, \quad (9.14)$$

where n represents the number of events. n_{dummy} represents the initial value used for the fit and does not have any meanings by itself; its value multiplied by μ_{CR} represents the fake lepton track yield in the CR. The transfer factors are then calculated by taking the ratio of normalization factors of CR-A and CR-B as illustrated in Fig. 7.3. When the number of dummy events are set equally for CR-A and CR-B, the ratio of the normalization factors equals to the actual ratio of the number of events, hence the transfer factor:

$$\frac{\mu_{\text{CR-A}}}{\mu_{\text{CR-B}}} = \frac{n_{\text{data}}^{\text{CR-A}} - n_{\text{trueLep}}^{\text{CR-A}}}{n_{\text{dummy}}^{\text{CR-A}}} \cdot \frac{n_{\text{dummy}}^{\text{CR-B}}}{n_{\text{data}}^{\text{CR-B}} - n_{\text{trueLep}}^{\text{CR-B}}} = \frac{n_{\text{data}}^{\text{CR-A}} - n_{\text{trueLep}}^{\text{CR-A}}}{n_{\text{data}}^{\text{CR-B}} - n_{\text{trueLep}}^{\text{CR-B}}} \equiv \text{TF}. \quad (9.15)$$

The number of fake lepton component in SR, hereinafter denoted as $n_{\text{fakeLep}}^{\text{SR}}$, is then obtained by multiplying the transfer factor to the fitted number of events in CR-C:

$$n_{\text{fakeLep}}^{\text{SR}} = (n_{\text{data}}^{\text{CR-C}} - n_{\text{trueLep}}^{\text{CR-C}}) \cdot \text{TF} = \mu_{\text{CR-C}} \cdot n_{\text{dummy}}^{\text{CR-C}} \cdot \text{TF}. \quad (9.16)$$

Finally, the total estimated background events in SR $n_{\text{totalEst}}^{\text{SR}}$ is obtained by adding the fake lepton component estimated by the data-driven method and the true lepton component estimated by MC simulation:

$$n_{\text{totalEst}}^{\text{SR}} = n_{\text{fakeLep}}^{\text{SR}} + n_{\text{trueLep}}^{\text{SR}}. \quad (9.17)$$

In the fit, $\mu_{\text{CR-A}}$, $\text{TF} = \mu_{\text{CR-A}}/\mu_{\text{CR-B}}$ and $\mu_{\text{CR-C}}$ are the fit parameters and thus, the transfer factors are obtained within the fit framework. The same procedures are performed for all VRs, following the diagrams illustrated in Fig. 7.4–7.6.

10. Results

This section shows and discusses the results of the statistical analysis, which has been described in Section 9.

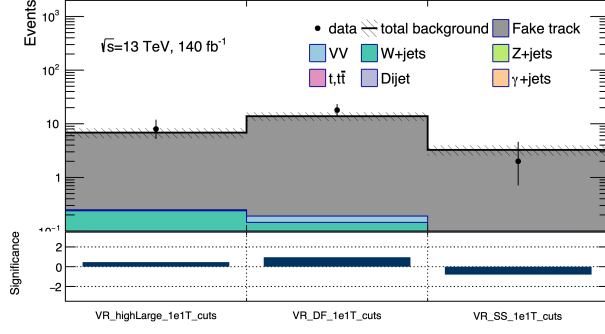
10.1 Background-only fit

Fits have been performed with the background-only hypothesis to obtain the expected number of SM background events in the SRs. The method has been first validated with dedicated VRs as described in Section 7.4. It must be noted that the fit has been performed for each of the six pNN- θ values for both electron and muon channels. Moreover, the relative uncertainty on the expected total background is larger for the muon channel, as the dominant non-closure uncertainty assigned to the muon channel is larger as mentioned in Section 8.3.

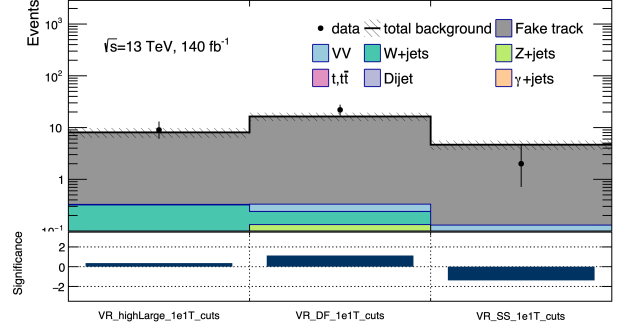
Fig. 10.1 and Fig. 10.2 show the agreement between observed data and estimated background yields in the VRs for each pNN- θ , for the electron channel and the muon channel, respectively. The deviation between the observed data and the estimated background has been quantified by the significance Z [174] defined as

$$Z = \begin{cases} +\sqrt{2\left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & (n \geq b) \\ -\sqrt{2\left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} & (n < b) \end{cases}, \quad (10.1)$$

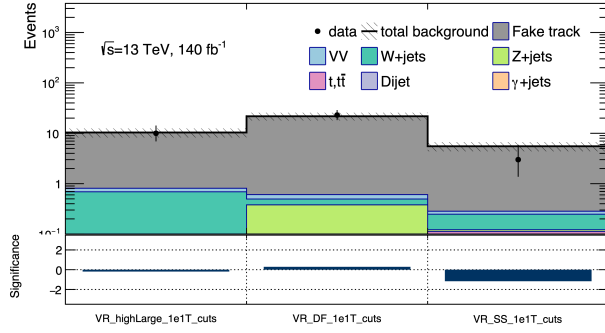
where n is the observed number of events, and $b \pm \sigma$ is the predicted number of events. The significance is within ± 2 , and the numbers of observed data and estimated background agree within errors for all VRs for both channels, thus assuring the validity of the background estimation method.



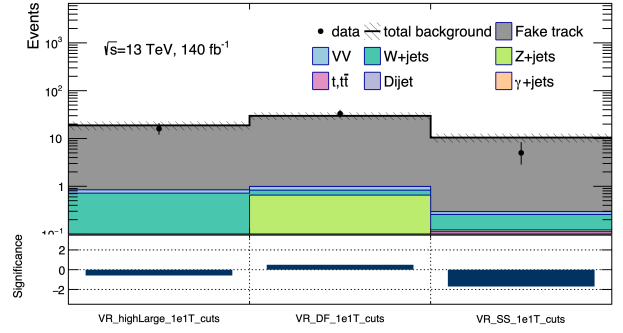
(a) $pNN-\theta = 1 \text{ GeV}$



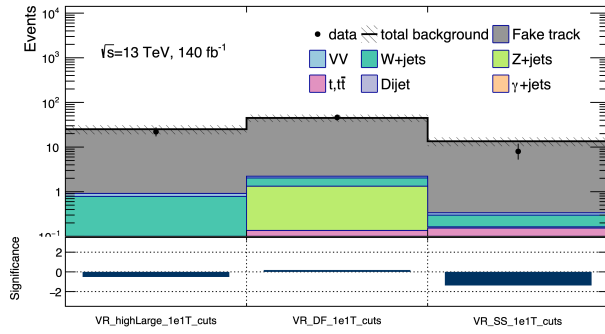
(b) $pNN-\theta = 1.5 \text{ GeV}$



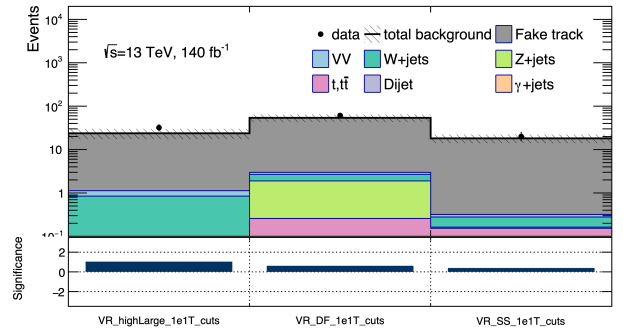
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

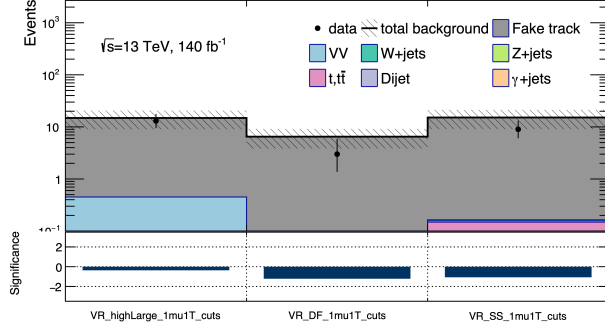


(e) $pNN-\theta = 4 \text{ GeV}$

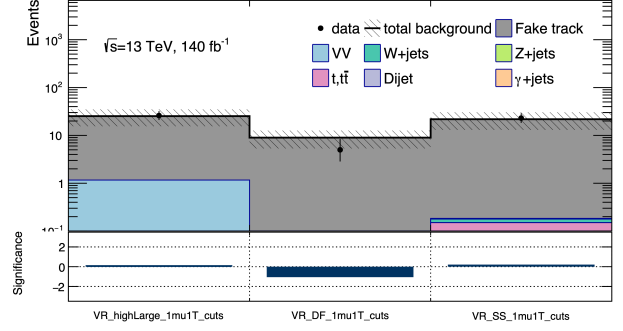


(f) $pNN-\theta = 5 \text{ GeV}$

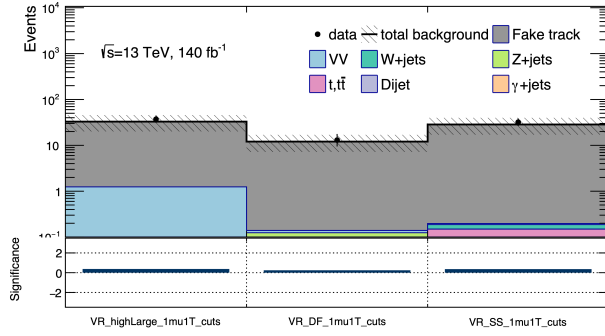
Figure 10.1: Agreement between observed data and estimated background yields in VRs for the electron channel. From the left side, the bins represent the agreement in VR-highLarge, VR-DF, and VR-SS, respectively. Data and estimation in all VRs agree within errors.



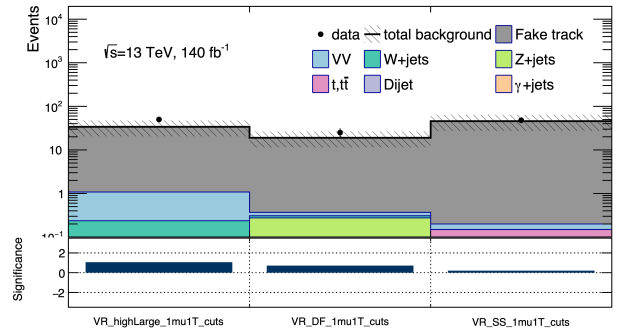
(a) $pNN-\theta = 1 \text{ GeV}$



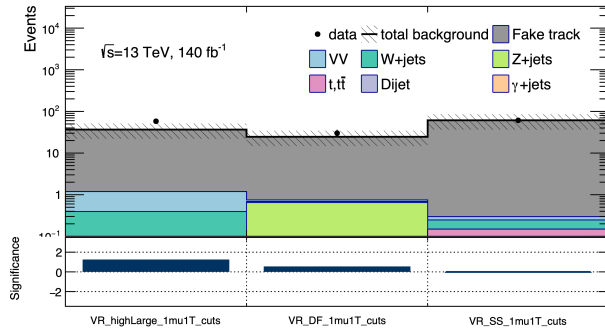
(b) $pNN-\theta = 1.5 \text{ GeV}$



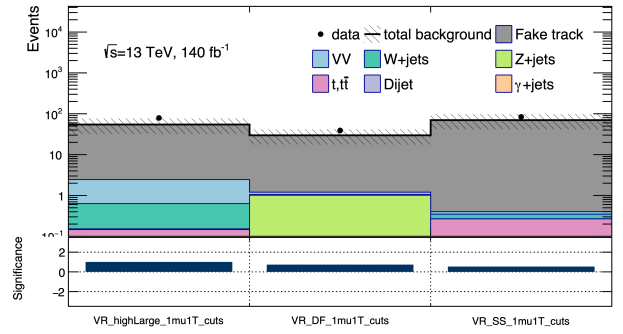
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$



(e) $pNN-\theta = 4 \text{ GeV}$



(f) $pNN-\theta = 5 \text{ GeV}$

Figure 10.2: Agreement between observed data and estimated background yields in VRs for the muon channel. From the left side, the bins represent the agreement in VR-highLarge, VR-DF, and VR-SS, respectively. Data and estimation in all VRs agree within errors.

Since it has been verified that the background estimation method is valid, data yields in the SRs for all pNN configurations have been unblinded. Tables 10.1–10.6 and 10.7–10.12 show the observed and expected yields in SR and CRs for the electron channel and the muon channel, respectively. In all SRs and CRs, the most dominant background is the fake lepton track contribution, which has been estimated by the data-driven method described in Section 7.2. Slight contributions from true lepton track background is also observed in the SRs, originating from diboson and V +jets processes. Figs 10.3 and 10.4 show the agreement between the observed and expected yields in the SRs, with the significance Z shown in the bottom panels. It can be seen that the data and prediction agree well within $Z < 2$ in all SRs; no significant excess has been observed.

Table 10.1: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 1$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	1	65	36716	341
Total fitted SM events	1.43 ± 0.37	65.00 ± 8.08	36715.99 ± 190.13	341.00 ± 18.35
Fake e track	1.10 ± 0.28	62.55 ± 8.18	36714.70 ± 190.13	340.73 ± 18.35
Diboson true e track	0.22 ± 0.18	1.48 ± 0.95	0.63 ± 0.34	$0.20^{+0.22}_{-0.20}$
W +jets true e track	$0.10^{+0.14}_{-0.10}$	$0.31^{+0.31}_{-0.31}$	$0.44^{+0.56}_{-0.44}$	$0.07^{+0.10}_{-0.07}$
Z +jets true e track	0.00 ± 0.00	0.43 ± 0.26	0.22 ± 0.11	0.00 ± 0.00
Others	0.00 ± 0.00	0.21 ± 0.13	0.00 ± 0.00	0.00 ± 0.00

Table 10.2: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 1.5$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	2	61	36028	401
Total fitted SM events	2.44 ± 0.56	60.84 ± 7.84	36027.73 ± 189.49	401.01 ± 20.03
Fake e track	1.93 ± 0.48	58.41 ± 7.95	36026.63 ± 189.49	400.72 ± 20.03
Diboson true e track	0.42 ± 0.28	1.48 ± 0.94	0.47 ± 0.25	$0.20^{+0.21}_{-0.20}$
W +jets true e track	$0.10^{+0.13}_{-0.10}$	$0.24^{+0.29}_{-0.24}$	$0.40^{+0.56}_{-0.40}$	$0.07^{+0.10}_{-0.07}$
Z +jets true e track	0.00 ± 0.00	0.49 ± 0.27	0.22 ± 0.10	0.00 ± 0.00
Others	0.00 ± 0.00	0.21 ± 0.13	0.00 ± 0.00	0.00 ± 0.00

Table 10.3: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 2$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	7	62	35207	504
Total fitted SM events	4.41 ± 0.92	62.00 ± 17.77	35207.00 ± 186.77	504.00 ± 22.35
Fake e track	3.65 ± 0.83	59.87 ± 6.80	35206.03 ± 186.78	503.70 ± 22.35
Diboson true e track	0.65 ± 0.42	1.39 ± 0.95	0.41 ± 0.24	0.22 ± 0.22
W +jets true e track	$0.10^{+0.13}_{-0.10}$	0.00 ± 0.00	$0.33^{+0.53}_{-0.33}$	$0.07^{+0.10}_{-0.07}$
Z +jets true e track	$0.00^{+0.01}_{-0.00}$	0.23 ± 0.19	0.20 ± 0.10	0.00 ± 0.00
Others	0.00 ± 0.00	0.21 ± 0.14	0.00 ± 0.00	0.00 ± 0.00

Table 10.4: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 3$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	7	58	33547	554
Total fitted SM events	8.44 ± 1.78	58.00 ± 7.67	33547.00 ± 183.17	554.00 ± 23.54
Fake e track	7.64 ± 1.76	56.46 ± 7.74	33546.11 ± 183.17	553.68 ± 23.54
Diboson true e track	0.67 ± 0.43	1.17 ± 0.88	0.41 ± 0.31	0.24 ± 0.21
W +jets true e track	$0.10^{+0.13}_{-0.10}$	$0.29^{+0.52}_{-0.29}$	$0.33^{+0.52}_{-0.33}$	$0.07^{+0.10}_{-0.07}$
Z +jets true e track	0.02 ± 0.02	0.14 ± 0.12	0.12 ± 0.07	0.00 ± 0.00
Others	0.00 ± 0.00	0.21 ± 0.15	0.00 ± 0.00	0.00 ± 0.00

Table 10.5: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 4$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	6	50	33870	340
Total fitted SM events	9.88 ± 2.36	49.98 ± 7.05	33870.26 ± 182.80	339.94 ± 18.33
Fake e track	8.61 ± 2.24	49.12 ± 7.07	33869.34 ± 182.84	339.75 ± 18.33
Diboson true e track	0.78 ± 0.53	0.49 ± 0.34	0.52 ± 0.34	0.09 ± 0.09
W +jets true e track	$0.41^{+0.43}_{-0.41}$	0.07 ± 0.07	$0.33^{+0.53}_{-0.33}$	$0.07^{+0.09}_{-0.07}$
Z +jets true e track	0.09 ± 0.07	$0.05^{+0.08}_{-0.05}$	0.06 ± 0.04	$0.02^{+0.03}_{-0.02}$
Others	0.00 ± 0.00	0.21 ± 0.15	0.00 ± 0.00	0.00 ± 0.00

Table 10.6: Observed and expected event yields for SR and CRs for the electron channel, pNN- $\theta = 5$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	7	47	34932	214
Total fitted SM events	5.76 ± 1.75	46.84 ± 6.89	34932.39 ± 187.54	214.08 ± 14.69
Fake e track	4.74 ± 1.66	46.39 ± 6.90	33931.54 ± 187.54	213.85 ± 14.69
Diboson true e track	0.65 ± 0.44	0.38 ± 0.30	0.66 ± 0.39	0.09 ± 0.09
W +jets true e track	$0.12^{+0.14}_{-0.12}$	$0.02^{+0.03}_{-0.02}$	0.12 ± 0.11	$0.07^{+0.09}_{-0.07}$
Z +jets true e track	0.25 ± 0.20	$0.03^{+0.05}_{-0.03}$	0.07 ± 0.04	$0.06^{+0.18}_{-0.06}$
Others	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Table 10.7: Observed and expected event yields for SR and CRs for the muon channel, pNN- $\theta = 1$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	6	365	31872	473
Total fitted SM events	6.54 ± 2.39	365.15 ± 19.20	31872.13 ± 179.13	472.98 ± 21.82
Fake μ track	5.74 ± 2.34	358.48 ± 19.36	31867.79 ± 179.14	472.15 ± 21.83
Diboson true μ track	0.79 ± 0.53	3.79 ± 1.54	2.79 ± 1.19	0.82 ± 0.46
W +jets true μ track	0.00 ± 0.00	0.98 ± 0.88	$0.10^{+0.13}_{-0.10}$	0.00 ± 0.00
Z +jets true μ track	0.01 ± 0.01	1.58 ± 0.65	0.71 ± 0.33	0.00 ± 0.00
Others	0.00 ± 0.00	0.32 ± 0.18	0.73 ± 0.33	0.00 ± 0.00

Table 10.8: Observed and expected event yields for SR and CRs for the muon channel, $p_{NN}-\theta = 1.5$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	11	341	30386	866
Total fitted SM events	12.06 ± 4.44	340.99 ± 18.48	30385.83 ± 174.31	865.96 ± 29.43
Fake μ track	10.80 ± 4.39	335.65 ± 18.60	30381.85 ± 174.32	864.85 ± 29.43
Diboson true μ track	1.25 ± 0.78	2.69 ± 1.09	2.44 ± 1.08	1.10 ± 0.55
W +jets true μ track	0.00 ± 0.00	1.00 ± 0.87	$0.11^{+0.13}_{-0.11}$	$0.00^{+0.01}_{-0.00}$
Z +jets true μ track	0.01 ± 0.01	1.45 ± 0.62	0.68 ± 0.31	0.00 ± 0.00
Others	0.00 ± 0.00	0.18 ± 0.10	0.73 ± 0.33	0.00 ± 0.00

Table 10.9: Observed and expected event yields for SR and CRs for the muon channel, $p_{NN}-\theta = 2$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	17	319	29114	1097
Total fitted SM events	17.06 ± 6.37	318.78 ± 17.93	29114.02 ± 170.63	1097.05 ± 33.13
Fake μ track	15.59 ± 6.33	314.06 ± 18.07	29110.76 ± 170.63	1095.79 ± 33.13
Diboson true μ track	1.33 ± 0.82	2.27 ± 0.97	2.05 ± 0.94	1.25 ± 0.58
W +jets true μ track	0.00 ± 0.00	$0.92^{+1.11}_{-0.92}$	0.10 ± 0.09	$0.00^{+0.01}_{-0.00}$
Z +jets true μ track	0.14 ± 0.12	1.34 ± 0.59	0.61 ± 0.29	$0.00^{+0.01}_{-0.00}$
Others	0.00 ± 0.00	0.18 ± 0.10	0.53 ± 0.23	0.00 ± 0.00

Table 10.10: Observed and expected event yields for SR and CRs for the muon channel, $p_{NN}-\theta = 3$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	22	274	27337	1004
Total fitted SM events	19.46 ± 7.20	274.01 ± 16.56	27336.87 ± 165.34	1004.00 ± 31.69
Fake μ track	17.47 ± 7.14	270.01 ± 16.64	27333.68 ± 165.34	1003.45 ± 31.69
Diboson true μ track	1.73 ± 1.03	2.30 ± 1.04	2.05 ± 0.83	0.53 ± 0.29
W +jets true μ track	$0.00^{+0.01}_{-0.00}$	0.42 ± 0.38	$0.04^{+0.05}_{-0.04}$	$0.00^{+0.01}_{-0.00}$
Z +jets true μ track	0.26 ± 0.19	1.09 ± 0.53	0.59 ± 0.26	0.02 ± 0.02
Others	0.00 ± 0.00	0.18 ± 0.11	0.53 ± 0.23	0.00 ± 0.00

Table 10.11: Observed and expected event yields for SR and CRs for the muon channel, $p_{NN}-\theta = 4$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	18	248	26762	717
Total fitted SM events	12.68 ± 4.65	248.07 ± 15.79	26762.00 ± 163.59	717.01 ± 26.78
Fake μ track	10.91 ± 4.60	244.41 ± 15.86	26758.85 ± 163.60	716.65 ± 26.78
Diboson true μ track	1.37 ± 0.82	2.28 ± 1.04	2.06 ± 0.88	0.30 ± 0.20
W +jets true μ track	$0.00^{+0.01}_{-0.00}$	0.26 ± 0.23	0.07 ± 0.06	0.05 ± 0.05
Z +jets true μ track	0.40 ± 0.26	0.77 ± 0.41	0.48 ± 0.24	0.00 ± 0.00
Others	0.00 ± 0.00	0.32 ± 0.20	0.53 ± 0.23	0.00 ± 0.00

Table 10.12: Observed and expected event yields for SR and CRs for the muon channel, $p_{\text{NN}}\text{-}\theta = 5$ GeV.

Yields	SR	CR-A	CR-B	CR-C
Observed	16	226	25873	488
Total fitted SM events	7.91 ± 3.25	226.00 ± 15.49	25873.00 ± 160.86	488.00 ± 22.10
Fake μ track	6.38 ± 3.14	223.96 ± 15.52	25869.82 ± 160.87	487.69 ± 22.10
Diboson true μ track	1.07 ± 0.65	1.10 ± 0.53	2.20 ± 1.12	0.22 ± 0.16
W +jets true μ track	0.00 ± 0.00	$0.35^{+0.50}_{-0.35}$	$0.04^{+0.05}_{-0.04}$	$0.00^{+0.01}_{-0.00}$
Z +jets true μ track	0.46 ± 0.30	0.38 ± 0.32	0.38 ± 0.22	0.08 ± 0.07
Others	0.00 ± 0.00	0.18 ± 0.11	0.53 ± 0.23	0.00 ± 0.00

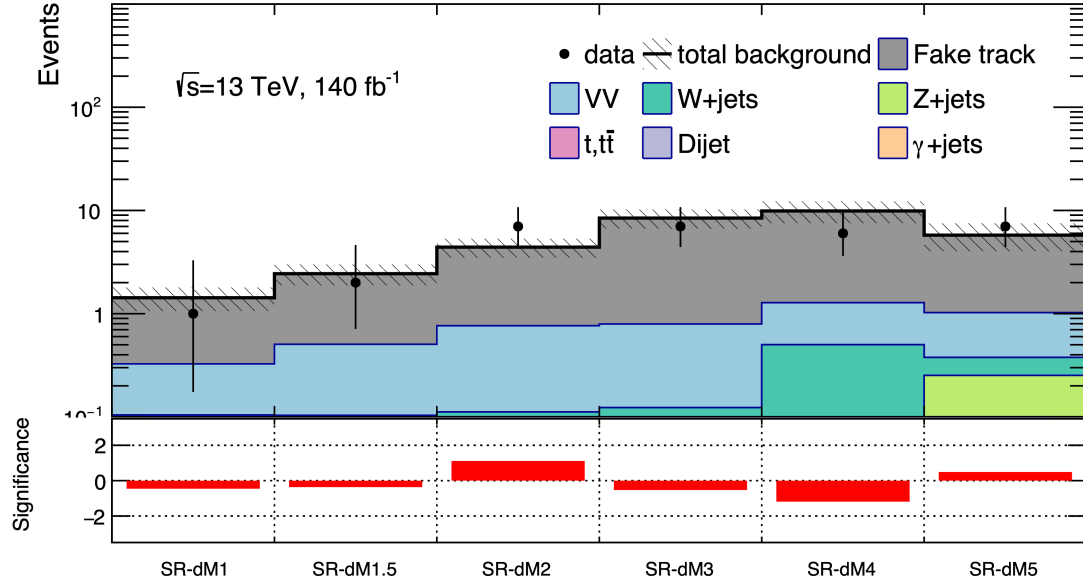


Figure 10.3: Agreement between observed data and estimated background yields in SRs for the electron channel. From the left side, the bins represent the agreement in SRs for $p_{\text{NN}}\text{-}\theta = 1, 1.5, 2, 3, 4$, and 5 GeV. The bottom panel shows the significance Z calculated by Eq. (10.1). The data and prediction agree well within $Z < 2$ in all SRs.

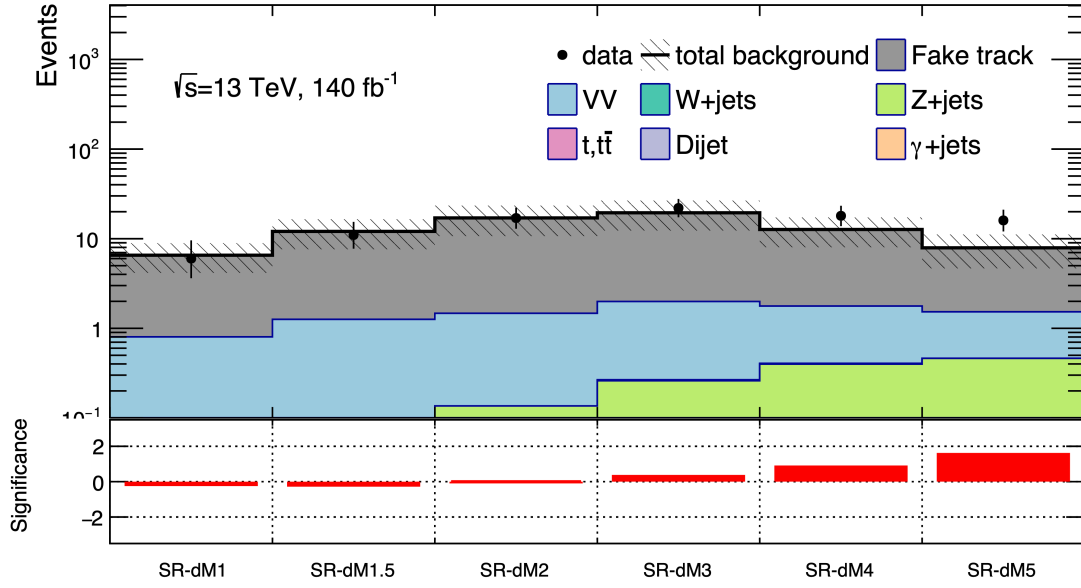
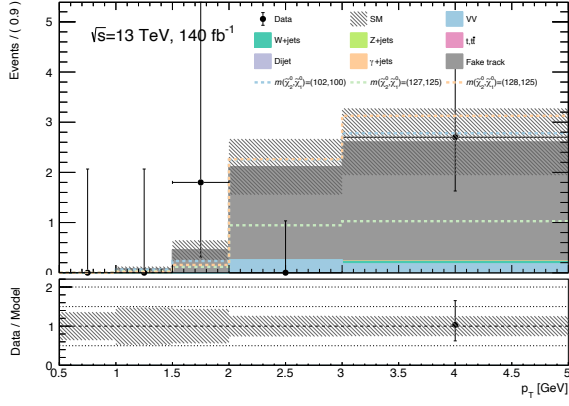
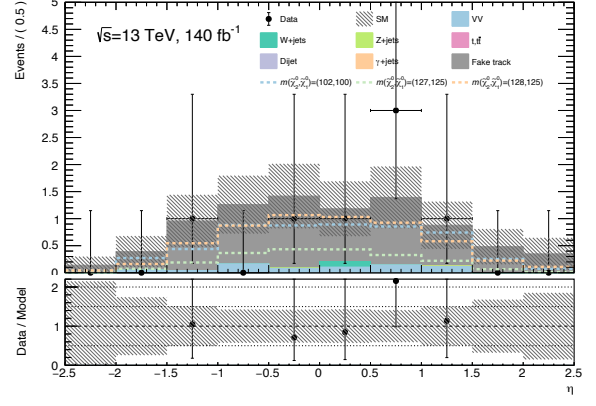


Figure 10.4: Agreement between observed data and estimated background yields in SRs for the muon channel. From the left side, the bins represent the agreement in SRs for $p_{NN}-\theta = 1, 1.5, 2, 3, 4$, and 5 GeV. The bottom panel shows the significance Z calculated by Eq. (10.1). The data and prediction agree well within $Z < 2$ in all SRs.

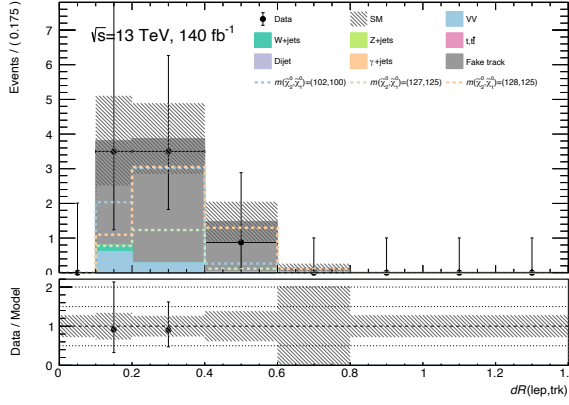
Furthermore, the kinematic distributions in the SRs have been checked. As examples, Fig. 10.5 and Fig. 10.6 show the kinematic distributions for some of the important variables for the electron channel and the muon channel, respectively for one $p_{NN}-\theta$. Good overall agreement within errors has been observed for both channels, and no significant discrepancies in the distributions have been seen.



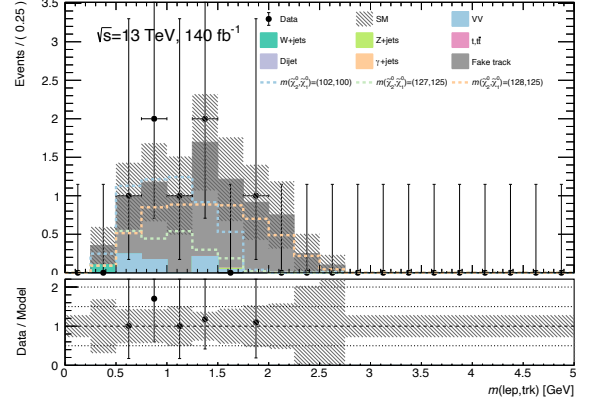
(a) Track p_T



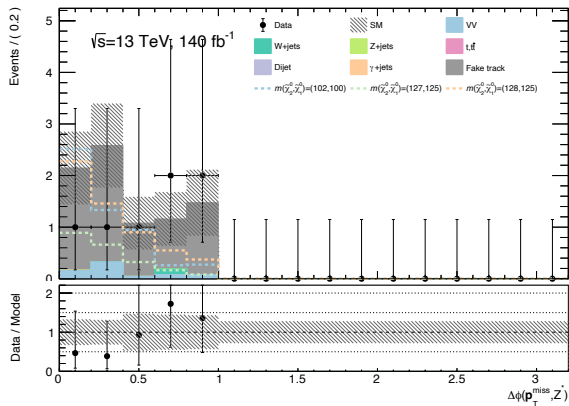
(b) Track η



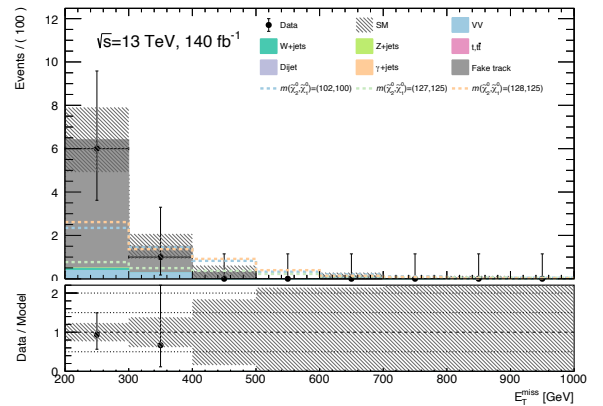
(c) $dR(\text{lep}, \text{trk})$



(d) $m(Z^*)$

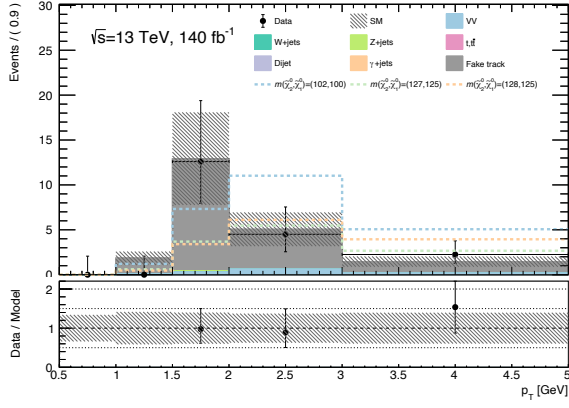


(e) $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$

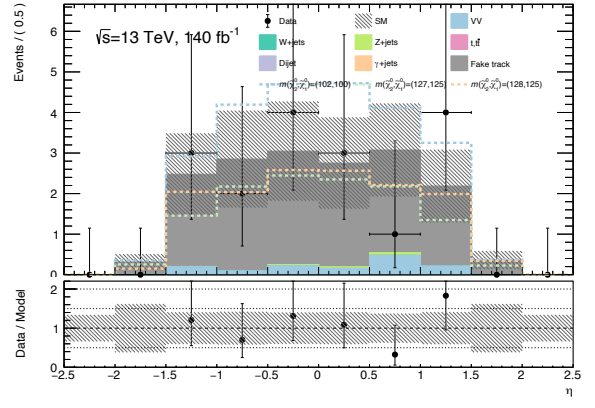


(f) E_T^{miss}

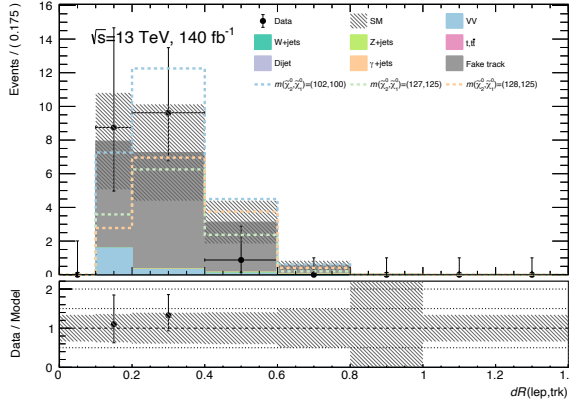
Figure 10.5: Kinematic distributions of data and estimated background in the SR for the electron channel, $p_{\text{NN}}\theta = 3$ GeV. Good overall agreement within errors has been observed, with low statistics taken into account. Signal distributions for $m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (102, 100)$, $(127, 125)$, and $(128, 125)$ GeV are also shown.



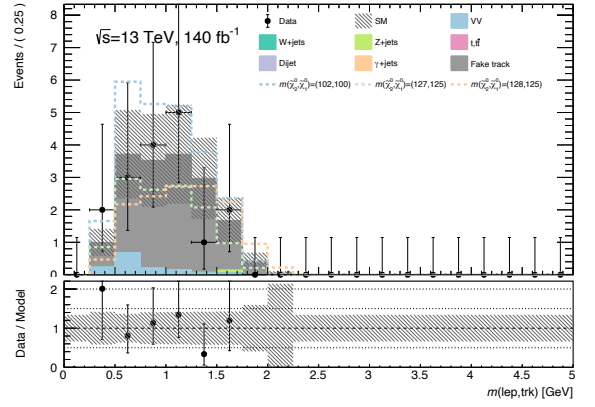
(a) Track p_T



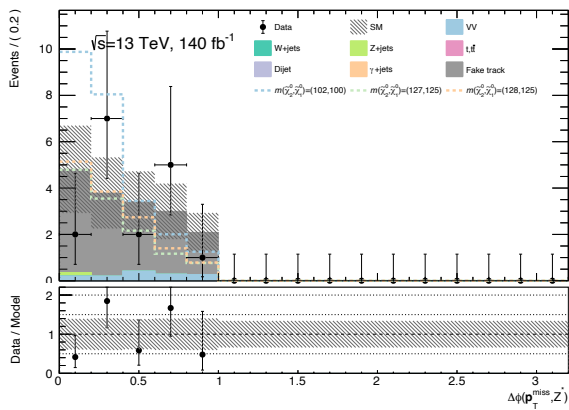
(b) Track η



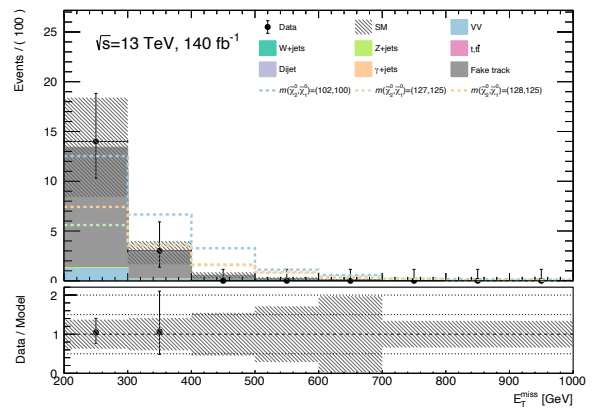
(c) $dR(\text{lep}, \text{trk})$



(d) $m(Z^*)$



(e) $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$



(f) E_T^{miss}

Figure 10.6: Kinematic distributions of data and estimated background in the SR for the muon channel, $p_{\text{NN}}\theta = 2$ GeV. Good overall agreement within errors has been observed between data and prediction. Signal distributions for $m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (102, 100), (127, 125),$ and $(128, 125)$ GeV are also shown.

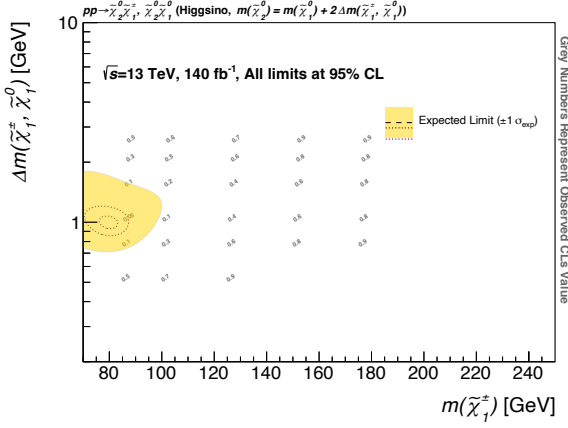
10.2 Model-dependent fit

Since no significant excess has been observed in all SRs, model-dependent fits have been performed to set exclusion limits on the target signal models, described in Sections 1.3.1 and 3.3.1. The fits have been performed for both electron and muon channels with all six pNN- θ s: 1, 1.5, 2, 3, 4, and 5 GeV. Fig. 10.7 and Fig. 10.8 show the observed and expected exclusion limits for each pNN- θ for electron and muon channels, respectively. All of the exclusion limits are at 95% confidence level and are shown in the $m(\tilde{\chi}_1^\pm) = \frac{1}{2}\{m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)\}$ vs $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ plane for easy comparison with results from other searches.

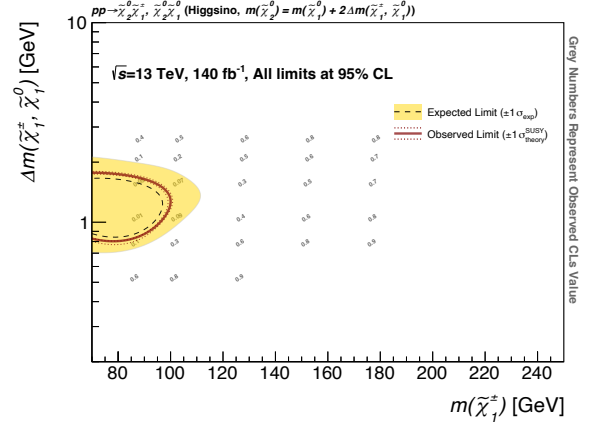
Moreover, the six pNN- θ s have been combined to draw a single exclusion contour for each channel. As these SRs could have possible overlaps, the envelope of the six contours has been taken by adopting the pNN- θ with the smallest expected CL_s value for each of the signal mass points. Fig. 10.9 shows the observed and expected exclusion limits obtained by combining the six pNN- θ s for each channel. For the electron channel, slight excess in data for pNN- $\theta = 2$ GeV and slight deficit in data for pNN- $\theta = 4$ GeV have resulted in a rather distorted observed limit with respect to the expected limit. For the muon channel, slight excess in data for pNN- $\theta = 4$ GeV and pNN- $\theta = 5$ GeV have resulted in a looser limit for higher mass splitting values.

Up to this point, the electron and muon channels have been analyzed and evaluated separately, however, as these channels are orthogonal to each other, they can be statistically combined by performing channel inclusive fits. Channel inclusive fits have been performed for the six pNN- θ configurations, and the configurations have been combined by the above method. Fig. 10.10 shows the observed and expected exclusion limits for each pNN- θ for the channel inclusive fits, and Fig. 10.11 shows the pNN combined observed and expected exclusion limits of the channel inclusive fits. The observed limit and the exclusion limit is similar for the channel inclusive fit due to coincidental effects; the effect of excess observed in the higher mass splitting values for the muon channel has been complemented by the effect of deficit observed in similar regions for the electron channel. The final observed exclusion limit, obtained from the statistical combination of both electron and muon channels and the combination of six pNN- θ s, extends beyond $m(\tilde{\chi}_1^\pm) = 130$ GeV for compressed mass regions with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1\text{--}2$ GeV, which have never been explored by experiments at the LHC.

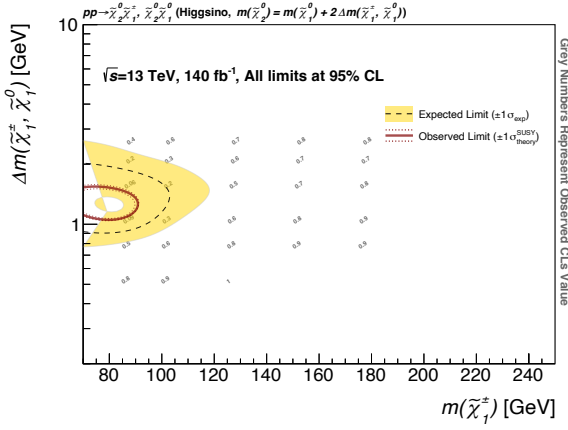
Fig. 10.12 shows the pNN combined observed and expected exclusion limits overlaid on results observed by existing analyses. It can be seen that the search presented in this dissertation plays a crucial role of searching the gap between the previous soft 2L search and the displaced track search.



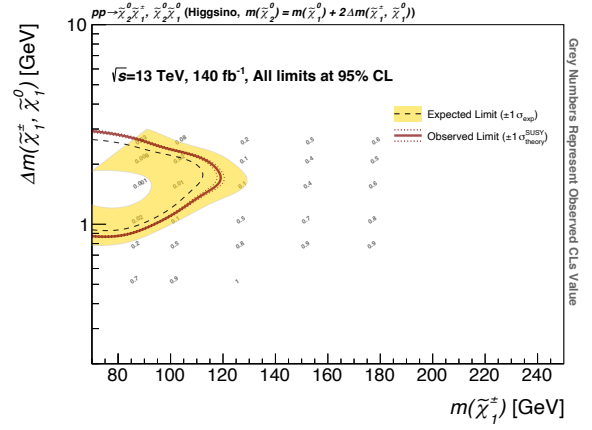
(a) pNN- $\theta = 1$ GeV



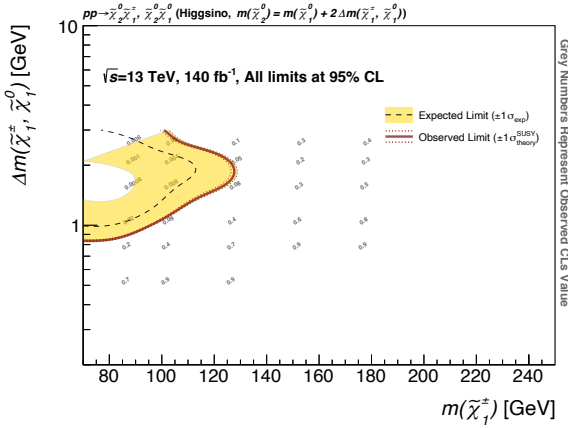
(b) pNN- $\theta = 1.5$ GeV



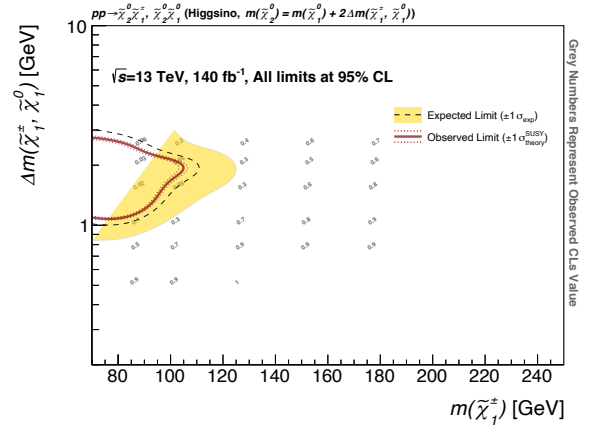
(c) pNN- $\theta = 2$ GeV



(d) pNN- $\theta = 3$ GeV

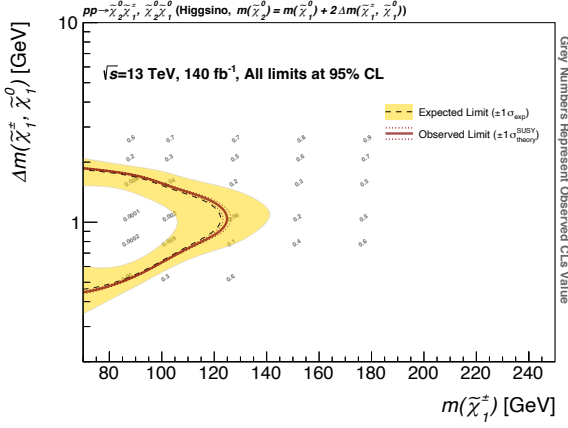


(e) pNN- $\theta = 4$ GeV

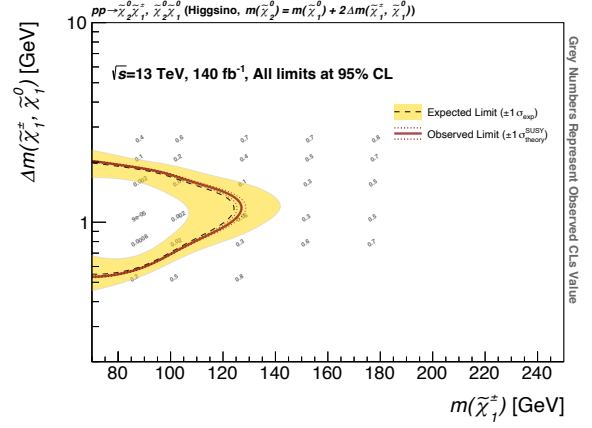


(f) pNN- $\theta = 5$ GeV

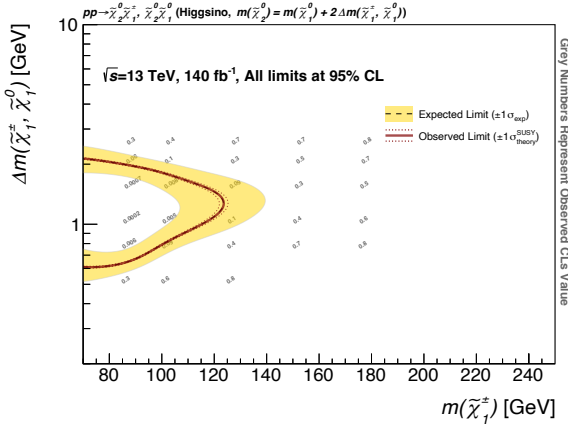
Figure 10.7: Observed and expected exclusion limits of the electron channel for each pNN- θ . The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.



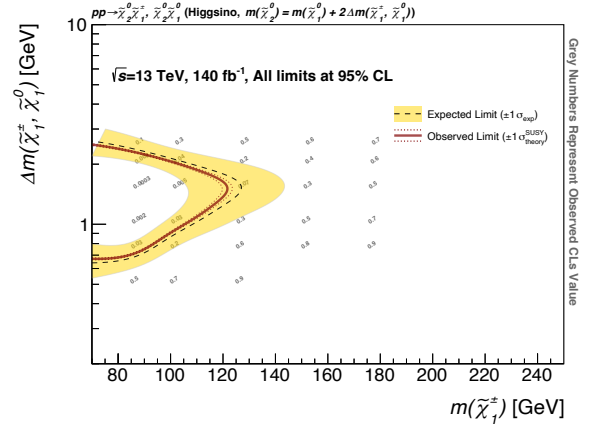
(a) pNN- $\theta = 1$ GeV



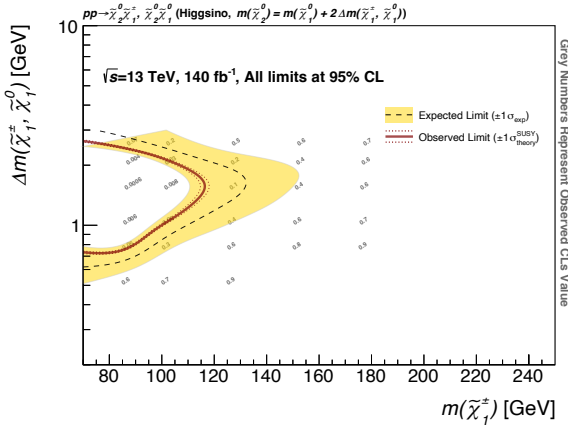
(b) pNN- $\theta = 1.5$ GeV



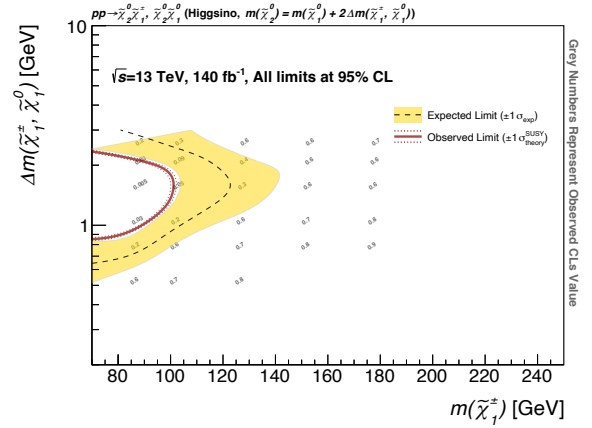
(c) pNN- $\theta = 2$ GeV



(d) pNN- $\theta = 3$ GeV

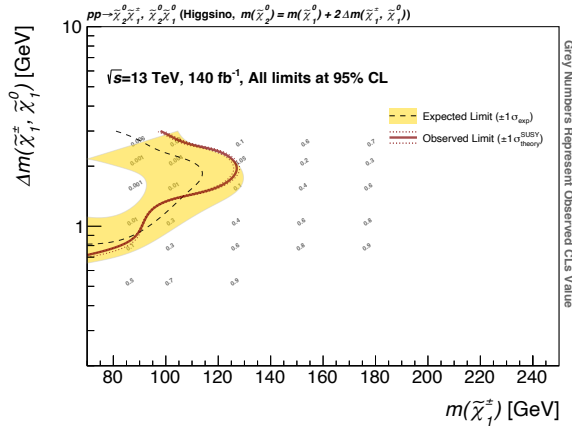


(e) pNN- $\theta = 4$ GeV

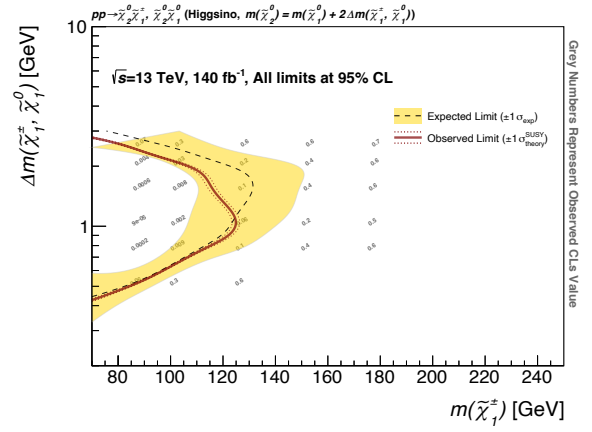


(f) pNN- $\theta = 5$ GeV

Figure 10.8: Observed and expected exclusion limits of the muon channel for each pNN- θ . The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.

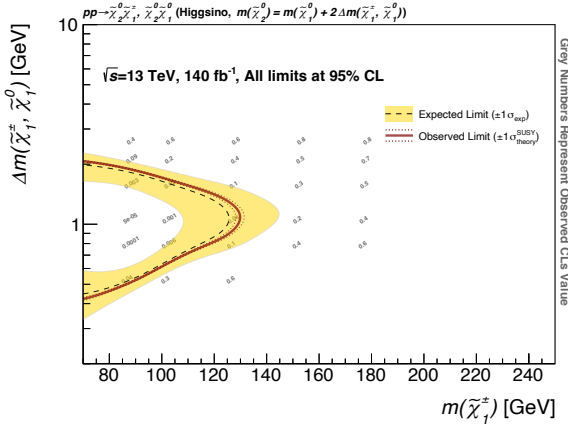


(a) Electron channel

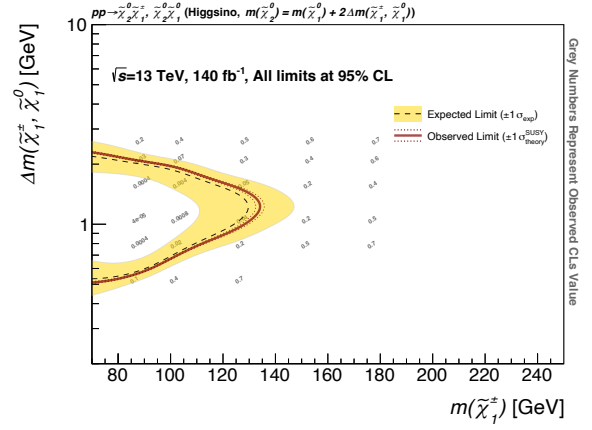


(b) Muon channel

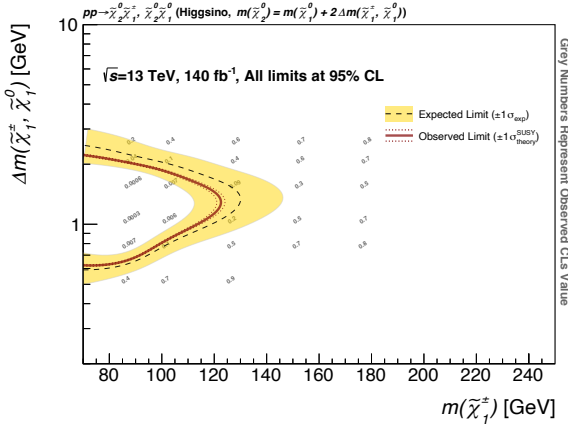
Figure 10.9: pNN combined observed and expected exclusion limits for electron and muon channels. The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.



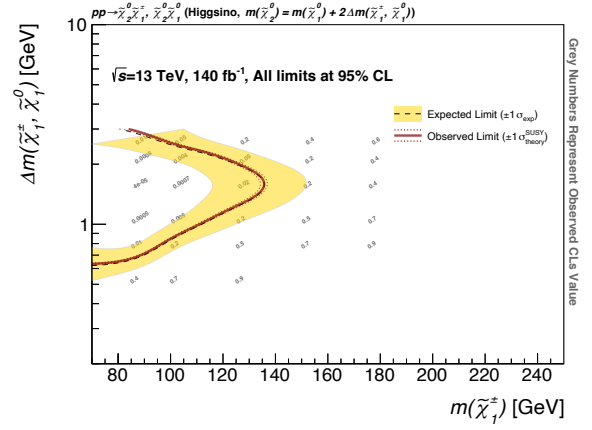
(a) pNN- $\theta = 1$ GeV



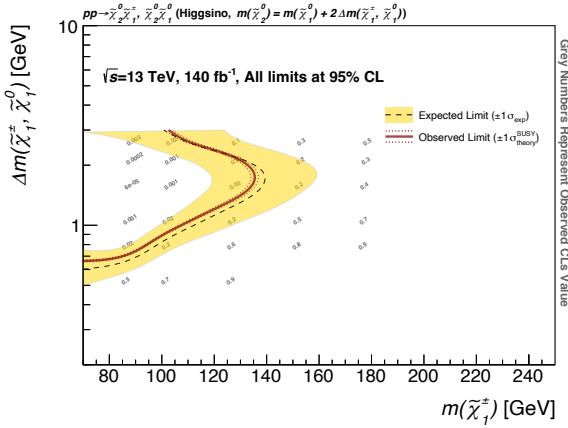
(b) pNN- $\theta = 1.5$ GeV



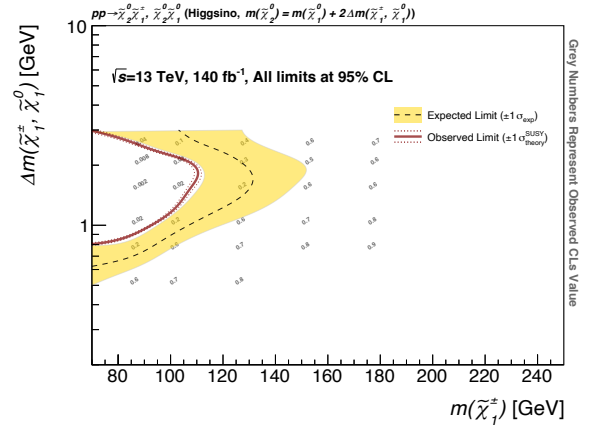
(c) pNN- $\theta = 2$ GeV



(d) pNN- $\theta = 3$ GeV



(e) pNN- $\theta = 4$ GeV



(f) pNN- $\theta = 5$ GeV

Figure 10.10: Channel inclusive observed and expected exclusion limits for each pNN- θ . The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.

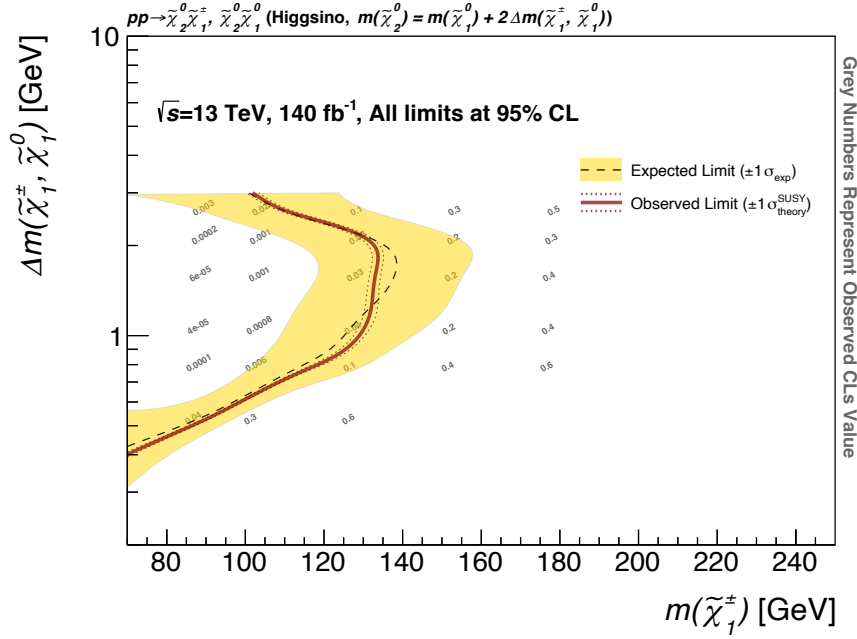


Figure 10.11: Channel inclusive pNN combined observed and expected exclusion limits. The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.

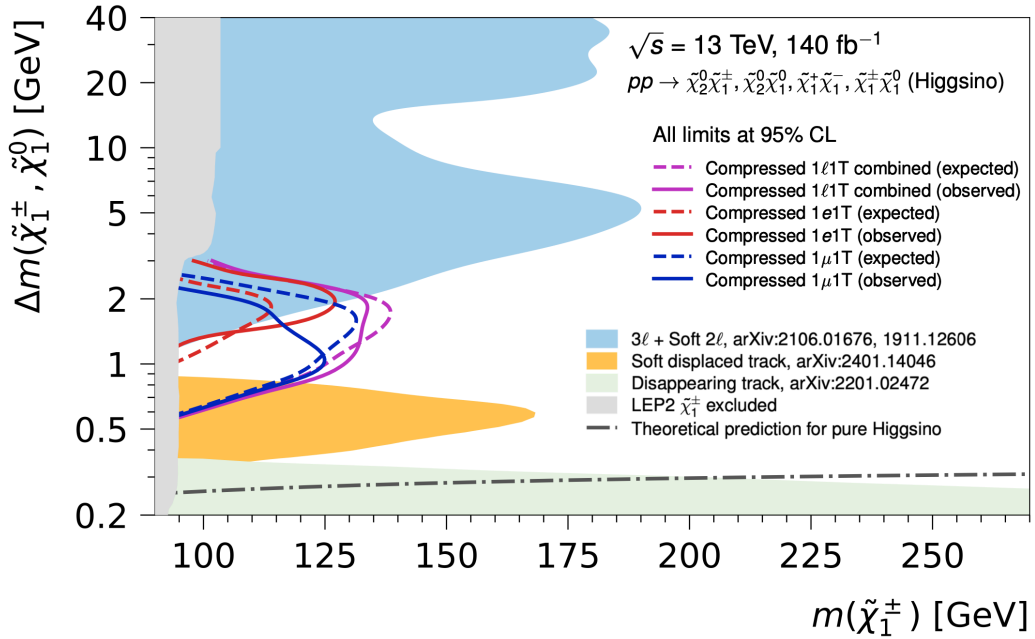


Figure 10.12: pNN combined observed and expected exclusion limits overlaid on observed results from existing analyses targeting higgsinos with compressed mass spectra. The red, blue, and violet solid (dashed) lines each represent pNN combined observed (expected) exclusion limit for the electron channel, the muon channel, and the combination of the two channels.

10.3 Model-independent fit

Model-independent fits have been performed to set upper limits on the number of BSM events in the target search regions, having an event topology with a high- p_T hadronic jet, large missing transverse momentum, a low- p_T lepton, and a very-low- p_T lepton-like track. For this purpose, as summarized in Table 10.13, three dedicated “discovery” SRs have been defined by combining the electron and muon channel SRs for three pNN- θ values: pNN- $\theta = 1, 3$, and 5 GeV, corresponding to small- Δm , mid- Δm and large- Δm . Each of them has been named as SR-small-dM, SR-mid-dM, and SR-large-dM.

Table 10.13: Summary of the discovery SRs. Three regions are defined by combining the electron and muon channel exclusion SRs for three pNN- θ values.

	SR-small-dM	SR-mid-dM	SR-large-dM
pNN- θ [GeV]	1	3	5

Fig. 10.13 shows the p -values as a function of signal strength μ_{sig} for each of the discovery SRs, obtained from the model-independent upper limit scans. Table 10.14 summarizes the model-independent upper limits obtained from these scans. For SR-small-dM, SR-mid-dM, and SR-large-dM, the observed upper limits on the cross section of BSM processes are 0.05 fb, 0.13 fb, and 0.14 fb, respectively.

Table 10.14: Model-independent upper limits for SR-small-dM, SR-mid-dM, and SR-large-dM.

	Observed	Expected	$\langle \epsilon \sigma \rangle_{\text{obs}}^{95} [\text{fb}]$	S_{obs}^{95}	S_{exp}^{95}	CL_b	$p(s=0) (Z)$
SR-small-dM	7	7.97 ± 2.42	0.05	7.5	$8.0^{+3.7}_{-2.2}$	0.41	0.50 (0.00)
SR-mid-dM	29	27.90 ± 7.42	0.13	18.6	$18.1^{+6.5}_{-4.7}$	0.55	0.50 (0.01)
SR-large-dM	23	13.67 ± 3.69	0.14	20.3	$12.7^{+5.3}_{-3.5}$	0.91	0.06 (1.52)

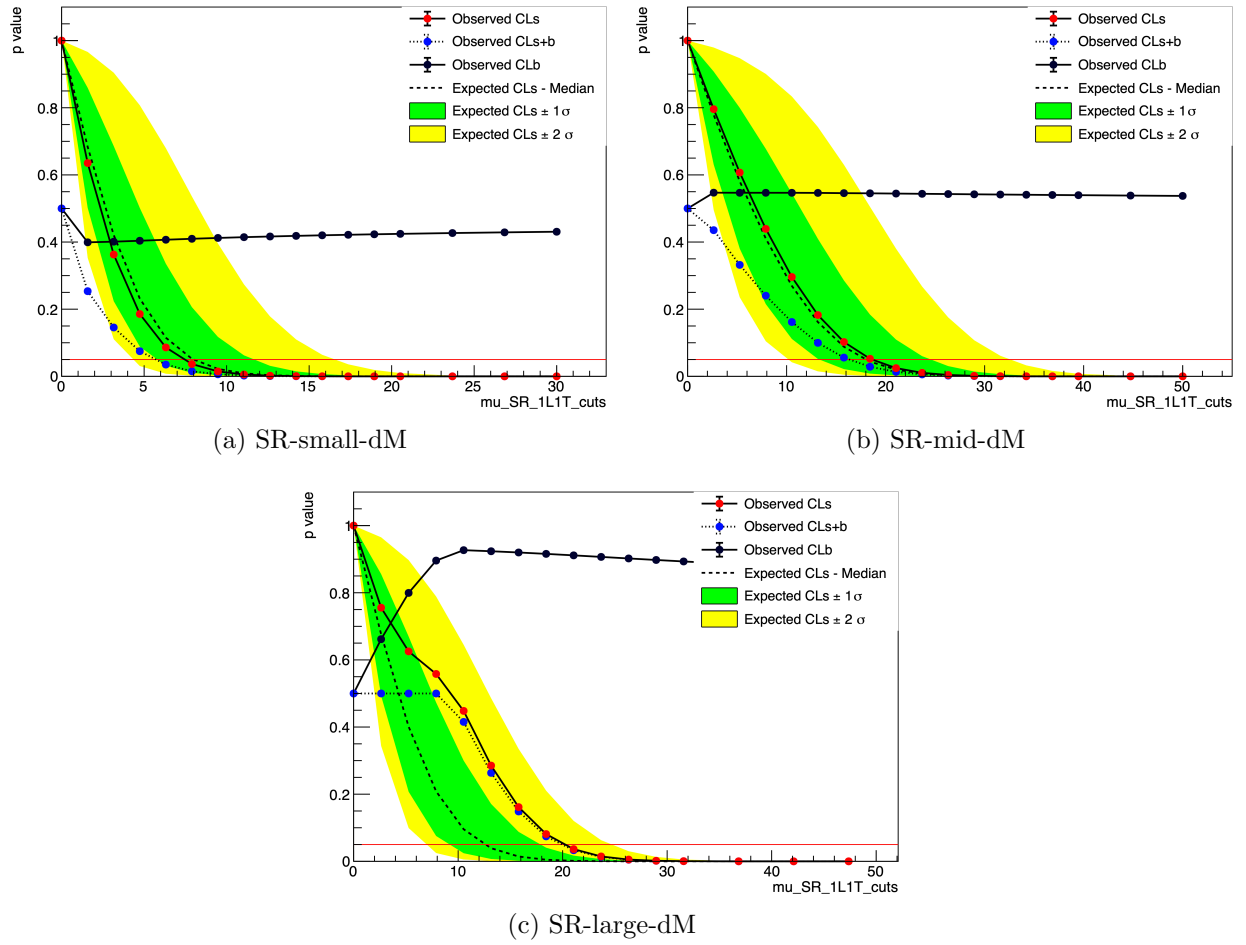


Figure 10.13: Observed CL_s , CL_{s+b} , and CL_b as a function of injected signal yield. Expected CL_s values with the $\pm 1\sigma$ and $\pm 2\sigma$ bands are also shown. The horizontal red line indicates the p -value at 0.05, corresponding to 95% confidence level.

11. Discussion

11.1 Slight excess observed for the muon channel

Although there was no *significant* excesses of observed data in any of the SRs, it can be seen in Fig. 10.4 that a slight excess of 1.5σ has been observed in the SRs of the muon channel for $p_{\text{NN}}\text{-}\theta = 5$ GeV. It is difficult to determine the source of this excess without additional statistics, however, some candidates of the source is discussed here.

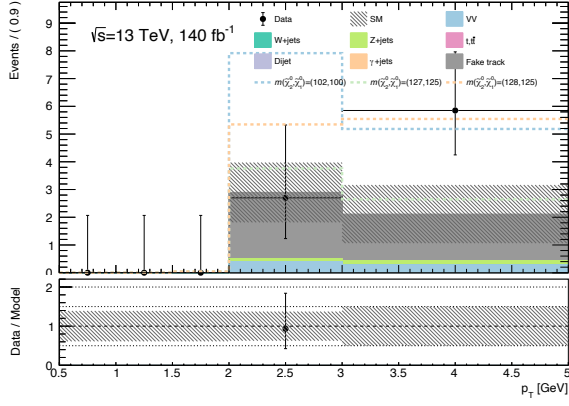
Fig. 11.1 shows some of the important kinematic distributions of the observed data and estimated background in the SR for the muon channel for $p_{\text{NN}}\text{-}\theta = 5$ GeV. It can be seen from these distributions that the excess comes from the high track p_{T} region, in particular, the region with $p_{\text{T}} = 3\text{--}5$ GeV. Dependencies on other variables have not been observed.

If the excess is from an actual BSM process, it is less-likely that it is from the targeted higgsino pair production signal. This is because, the mass region which $p_{\text{NN}}\text{-}\theta = 5$ GeV targets has large overlaps with the region which has already been excluded by the soft 2L search. Moreover, the electron channel does not present a similar excess; this is also incompatible with the higgsino signal hypothesis. Therefore, if one assumes that this excess is from BSM, it would likely be from another process involving the high- p_{T} jet + $E_{\text{T}}^{\text{miss}}$ topology, favoring the emission of low- p_{T} muons over low- p_{T} electrons. On the other hand, if the excess is from SM background, it is likely that the excess is from the dominant $W(\rightarrow \mu\nu)$ +jets background, in which a hadronic track from an underlying event is accidentally identified as a low- p_{T} muon track. However, hadronic tracks from underlying events tend to have lower p_{T} , so it is not fully clear why the excess gathers in the high track p_{T} regions. As mentioned earlier, more data would be necessary to further understand the source of this excess.

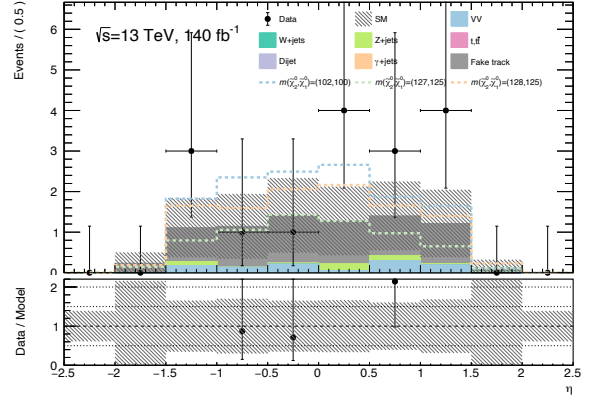
11.2 Comparison to previous approaches and other experiments

Comparison to the ATLAS soft 2L search

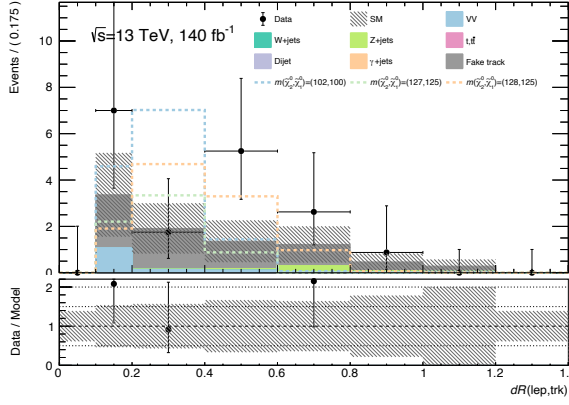
As shown in Fig. 10.12, the search presented in this dissertation has successfully explored the mass splitting region with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1\text{--}1.5$ GeV (or $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 2\text{--}3$ GeV) for the first time since the LEP2 experiment. Compared to the soft 2L search, which targets the same event topology with high- p_{T} hadronic jet, missing transverse momentum, and two low- p_{T} leptons from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ decay, this search has extended the search region



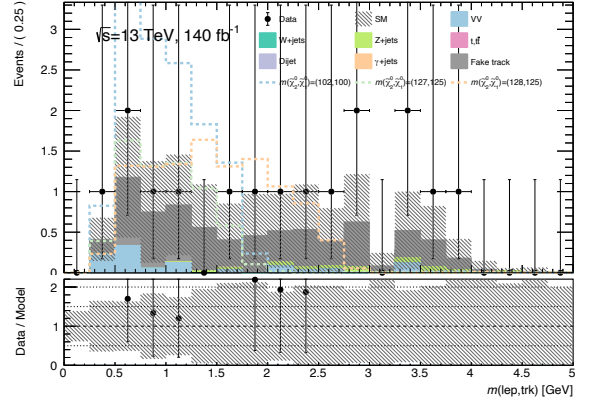
(a) Track p_T



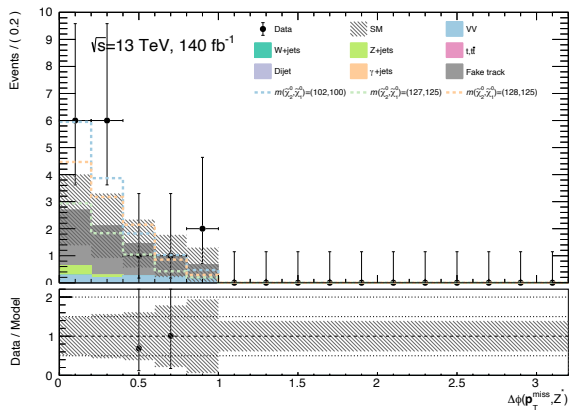
(b) Track η



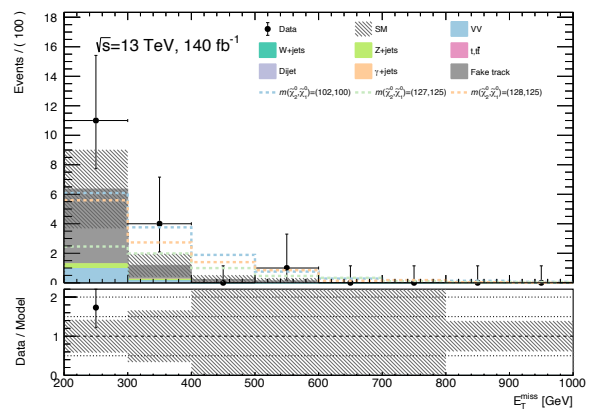
(c) $dR(\text{lep}, \text{trk})$



(d) $m(Z^*)$



(e) $\Delta\phi(\mathbf{p}_T^{\text{miss}}, Z^*)$



(f) E_T^{miss}

Figure 11.1: Kinematic distributions of data and estimated background in the SR for the muon channel, $p_{\text{NN}}\theta = 5$ GeV, which has the largest excess in this search. The excess comes from high track p_T region, namely from the 3–5 GeV bin.

down to smaller mass splitting regions by the combination of the two following efforts:

- Significant suppression of low- p_T fake lepton tracks by the development of low- p_T lepton track identification methods,
- More sophisticated signal and background separation by a pNN-based event selection method.

The soft 2L search required two standard leptons or one standard lepton plus an unidentified isolated track. The lower p_T bound for standard electrons and muons were 4.5 GeV and 3 GeV, respectively, which are the same as the standard lepton criteria used in this search. The event selection was performed by imposing uniform cuts on all considered mass points.

On the other hand, this search requires one standard lepton and one low- p_T lepton identified track, with lower p_T bounds reaching 0.5 GeV and 1 GeV for the electron channel and muon channel, respectively. The introduction of these algorithms contributes significantly to the suppression of low- p_T fake lepton tracks, which was also the main background of the one lepton plus one isolated track channel of the soft 2L search. Furthermore, the event selection of this search is performed by a pNN, considering the event topology dependencies on the mass splitting, as shown in Fig 6.4 and Fig. 6.5. Compared to the dominant W +jets background, the event topology differ more for smaller mass splitting values, which has also contributed to the increased sensitivity in the corresponding regions.

Comparison to the CMS experiment

The CMS experiment has also performed a higgsino search similar to the ATLAS soft 2L search [175]. Fig. 11.2 shows the exclusion limits set on simplified higgsino models set by the CMS experiment. Higgsino mass of up to 150 GeV has been excluded for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 3$ GeV, however, regions having smaller mass splittings have not been considered. Therefore, as of today, this search sets the most stringent limit on simplified higgsino models in the targeted mass regions of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\text{--}3$ GeV.

11.3 Interpretation in $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ vs $m(\tilde{\chi}_1^0)$

Although the results presented in Section 10.2 have assumed a simplified model with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ for easier comparison with previous search results, this search itself is independent of the mass of $\tilde{\chi}_1^\pm$. Hence, it is possible to apply the results to a wider range of supersymmetric models which do not assume the $\tilde{\chi}_1^\pm$ mass. In particular, in the limit where the bino and wino masses M_1 and M_2 are much larger than the higgsino mass parameter μ , higgsino mass splittings at tree-level can be approximated by the following [176]:

$$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = m_Z^2 \left(\frac{c_W^2}{M_2} + \frac{s_W^2}{M_1} \right) + \dots, \quad (11.1)$$

$$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = m_Z^2 \left\{ (1 - \sigma \sin 2\beta) \frac{c_W^2}{M_2} + (1 + \sigma \sin 2\beta) \frac{s_W^2}{M_1} \right\} + \dots, \quad (11.2)$$

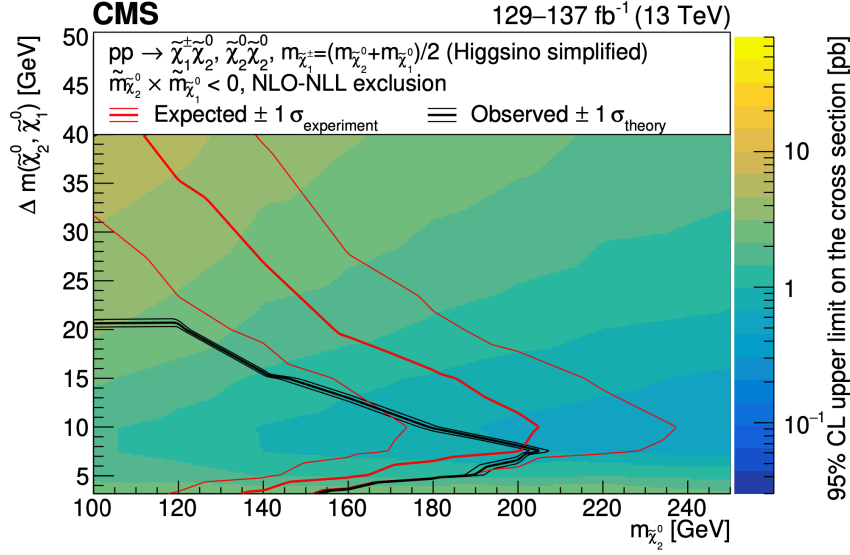
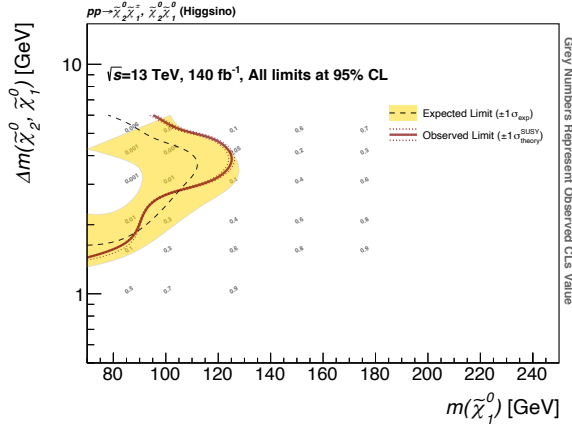


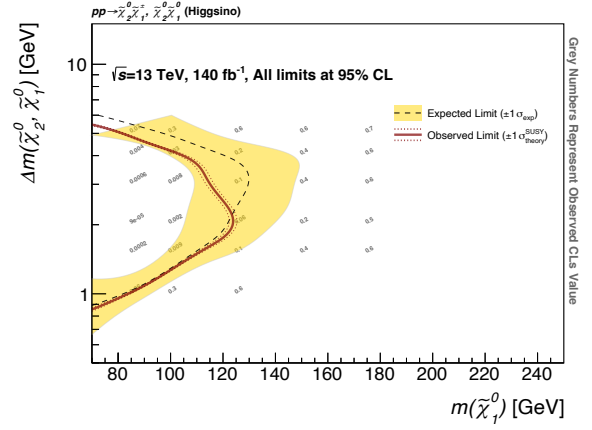
Figure 11.2: Exclusion limits set on simplified higgsino models by the CMS experiment [175]. Note that the lower bound on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ of this plot is 3 GeV; the mass region targeted by this search is not shown.

in which $c_W \equiv \cos \theta_W$, $s_W \equiv \sin \theta_W$, and $\sigma \equiv \text{sgn}(\mu)$. Only in the further limit of large $\tan \beta$ or when $M_1/M_2 = s_W^2/c_W^2$, the simplified assumption of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ holds. Thus, removing the $\tilde{\chi}_1^\pm$ mass assumption enables the search results to be interpreted also for supersymmetric models with smaller $\tan \beta$.

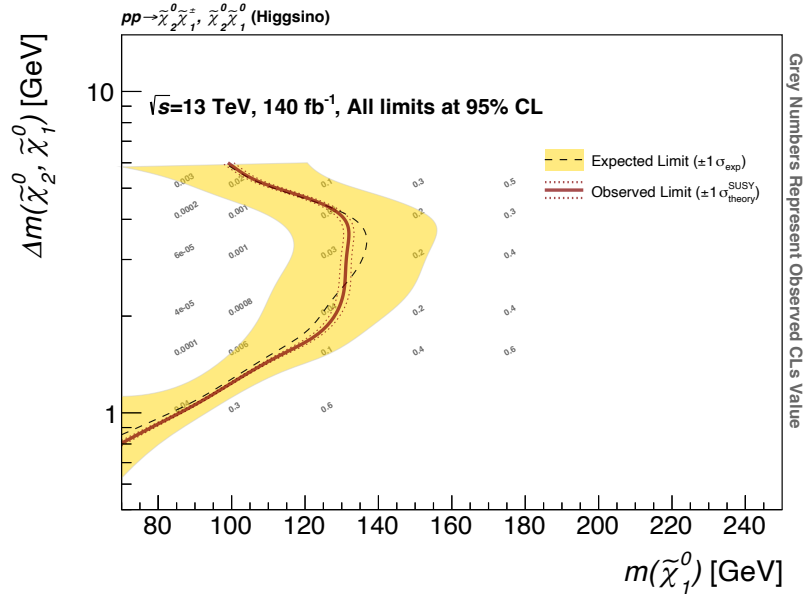
Fig. 11.3 shows the pNN combined exclusion limits in the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ vs $m(\tilde{\chi}_1^0)$ plane for the electron channel, muon channel, and combined. Each of them corresponds to Fig. 10.9a, Fig. 10.9b, and Fig. 10.11. For wider ranges of models without the assumption of $\tilde{\chi}_1^\pm$ mass, $m(\tilde{\chi}_1^0)$ of up to 130 GeV has been excluded in the mass splitting region of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\text{--}4$ GeV.



(a) Electron channel



(b) Muon channel



(c) Combined

Figure 11.3: pNN combined observed and expected exclusion limits in the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ vs $m(\tilde{\chi}_1^0)$ plane for the electron channel, muon channel, and combined. The red solid line and the dotted line show the observed exclusion limit and its one standard deviation from theoretical uncertainties, respectively. The black dashed line and the yellow band represent the expected exclusion limit and its one standard deviation, respectively. The grey numbers represent the expected CL_s value for each signal mass grid point.

11.4 Impact on SUSY mass parameters

As described in Section 1.2.3, the masses of the neutralinos are represented by the fundamental SUSY mass parameters μ , M_1 , and M_2 . Thus, the results shown in Section 11.3 can further be interpreted to examine the impact on these fundamental parameters.

In typical models such as NUHM models, the mass hierarchy relation are likely to satisfy $|\mu| < M_1 < M_2$. In such cases, the slight mixture of the bino component with the dominant higgsino component could lead to a non-trivial mass splitting value between the light mass eigenstates. Hence, in this interpretation, the impact of the wino component is assumed to be negligible; the relation $|\mu| \ll M_1 \ll M_2$ is assumed to examine the impact of the results on only the higgsino and bino mass parameters, μ and M_1 . Under such assumptions, the higgsino and bino mass parameters are given by

$$|\mu| = m(\tilde{\chi}_1^0) + \frac{1}{2}(1 + \sigma \sin 2\beta)\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0), \quad (11.3)$$

$$M_1 = m_Z^2 \frac{s_W^2}{\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)}. \quad (11.4)$$

Fig. 11.4 shows the interpretation of the results of this search in the fundamental mass parameter plane of μ vs M_1 , under the above assumptions. Since $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ is much smaller compared to $m(\tilde{\chi}_1^0)$, $|\mu|$ depends only slightly on $\tan\beta$ and σ according to Eq. (11.3); they have been set to $\tan\beta = 10$ and $\sigma = -1$ as a benchmark scenario. It has been observed that this search extends the limit on M_1 by about 1 TeV for $|\mu|$ below 130 GeV, compared to the previous soft 2L search. As mentioned in Section 11.3, the limits shown here do not depend on the mass of the charged higgsino $\tilde{\chi}_1^\pm$.

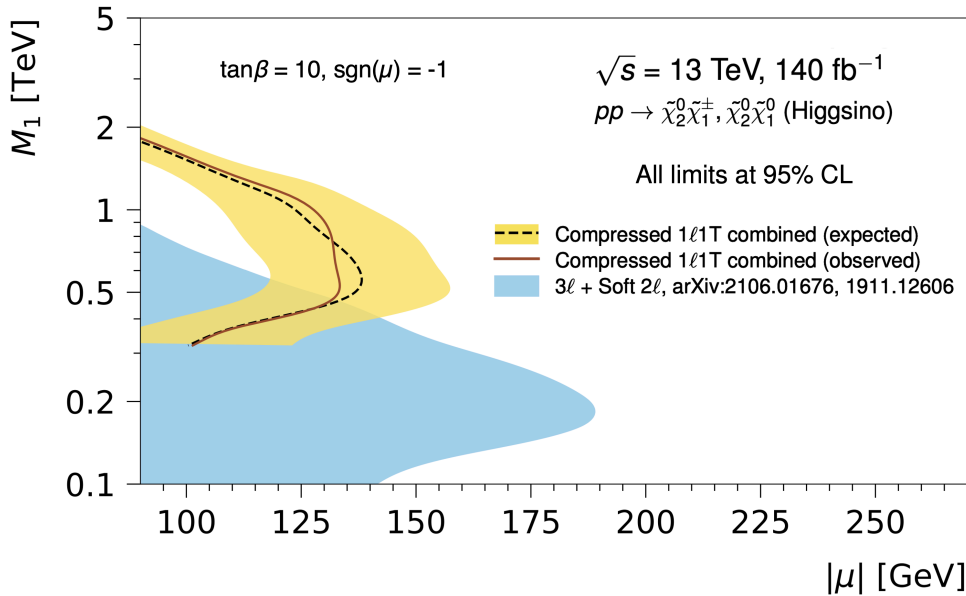


Figure 11.4: Interpretation of the search results in the μ vs M_1 plane. $|\mu| \ll M_1 \ll M_2$, $\tan\beta = 10$, and $\sigma \equiv \text{sgn}(\mu) = -1$ have been assumed for simplicity. This search extends the limit on M_1 by about 1 TeV.

11.5 Prospects in future experiments

The results presented in this dissertation uses the full LHC Run 2 dataset collected by the ATLAS experiment, corresponding to 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$. It is worthwhile to estimate the expected sensitivity of this search method in future experiments, especially with the ongoing LHC Run 3 and HL-LHC starting in 2029, to devise future search strategies. In this study, the performances of the low- p_T electron and muon track IDs in future experiments are assumed to be the same as LHC Run 2 for simplicity.

Expected sensitivities of this search in LHC Run 3 and HL-LHC have been evaluated as expected exclusion contours and discovery reaches by scaling the number of signal and background yields in the SRs. The scaling factors are comprised of two elements as summarized in Table 11.1: the integrated luminosity ratio and the cross section ratio. The signal cross sections have been estimated to rise by about 10(15)% by the transition from $\sqrt{s} = 13 \text{ TeV}$ to $\sqrt{s} = 13.6(14) \text{ TeV}$. The background cross sections have been estimated using those of the dominant W +jets processes; they are expected to increase by 5(8)% by the energy increase in Run 3 (HL-LHC). The final significance is calculated by the scaled signal yields, background yields, and the background uncertainties using Eq. (10.1). $Z > 1.645$, corresponding to 95% CL, is required for exclusion, and $Z > 5$ is required for discovery.

Table 11.1: Summary of the scaling factors used for evaluating the expected sensitivities for future experiments. The integrated luminosity factors are derived by simply taking the ratio over 140 fb^{-1} . The cross section ratios correspond to the expected increase by the increase of center-of-mass energy: $\sqrt{s} = 13.6 \text{ TeV}$ for LHC Run 3 and $\sqrt{s} = 14 \text{ TeV}$ for HL-LHC. Note that the 400 fb^{-1} of LHC Run 3 includes the Run 2 data of 140 fb^{-1} , thus the cross section factors have been applied only to the corresponding 260 fb^{-1} .

	LHC Run 3 (400 fb^{-1})	HL-LHC (3000 fb^{-1})	HL-LHC (4000 fb^{-1})
Integrated luminosity	2.86	21.4	28.6
Signal cross section	1.10	1.15	1.15
Background cross section	1.05	1.08	1.08

Fig. 11.5 shows the expected exclusion and discovery reach of this search in LHC Run 3 and HL-LHC, evaluated by the above method. In the case in which the higgsino does not exist in the corresponding search region, the exclusion limit is expected to reach up to higgsino mass of 160 GeV and 170 GeV for LHC Run 3 and HL-LHC, respectively. The expected discovery reaches for LHC Run 3 and HL-LHC both lie within the observed exclusion of the search presented in this dissertation; even if higgsinos exist in this target mass splitting region, they cannot be discovered by the ATLAS experiment with the same strategy. This gives out a significant message that further improvements in the analysis method are necessary to discover higgsinos in future LHC experiments.

Possible future improvements

Some improvements are proposed below for possible amelioration of the sensitivity to higgsinos in future experiments, using the low-momentum lepton signatures targeted in

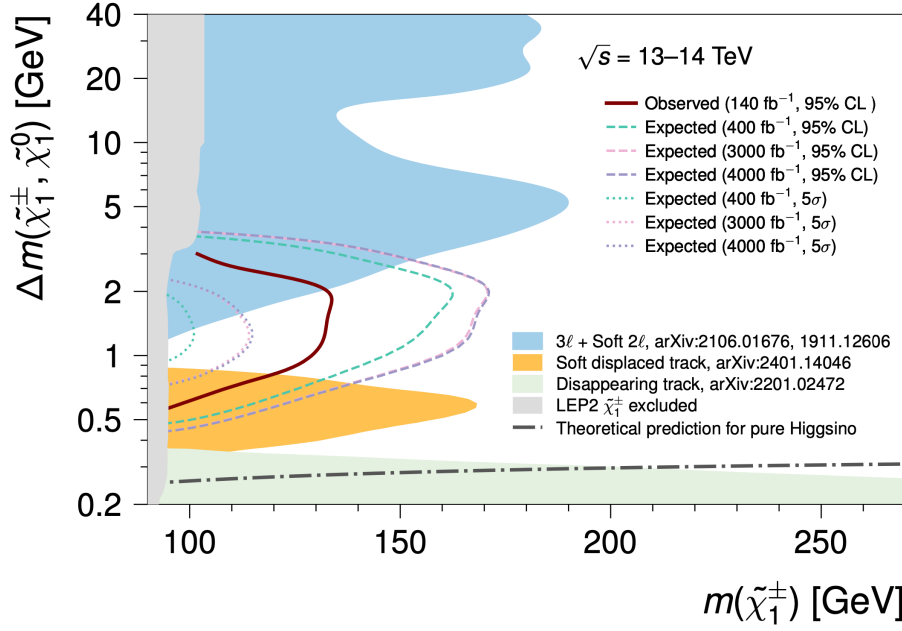


Figure 11.5: Expected exclusion and discovery reach of this search in LHC Run 3 and HL-LHC. The expected discovery reaches lie within the observed exclusion limit presented in this dissertation.

this search. The sensitivity of this search largely depends on the identification of the low-momentum leptons emitted from the neutral higgsino decay, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$. Therefore, the first-order improvements are expected to be of those related to the performance of low- p_T lepton identification:

- Improvement of the low- p_T lepton track identification,
- Improvement of the standard lepton identification, with possible extension to lower p_T regime,
- Addition of the $0\ell 2T$ channel.

The first item, the improvement of the low- p_T lepton track identification, is the most straightforward way of ameliorating the sensitivity of this search. This could be realized by adding further information as inputs to the low- p_T lepton track identification algorithms. For example, the shape information of the topo-clusters could be added for both electron and muon track identification, to further discriminate lepton-like tracks and hadron-like tracks.

The second item, the improvement of the standard lepton identification is also expected to have significant impact on the search. The current p_T threshold of 4.5 (3) GeV of the standard electron (muon) identification sets a stringent limit on this search, as signal leptons tend to have lower p_T for the target $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\text{--}3$ GeV region. However, as the standard electron and muon identification criteria have tighter requirements on the calorimeter energy thresholds and muon spectrometer hits, respectively, this item may be more difficult to achieve, at least in the ongoing LHC Run 3 due to similar detector performances.

The third item, the addition of the $0\ell 2T$ channel, could follow after the success of the first item. The requirement of the one standard ID lepton of this search is imposed to

achieve sufficient background reduction. If this could be achieved with the low- p_T lepton track identification algorithms, addition of a channel requiring no standardly identified lepton and two low- p_T lepton-like tracks, could result in further sensitivity.

In addition to the aforementioned items, improvement of the event selection method and statistical combinations with the 2L search and the displaced track search could also be considered. However, these improvements are expected to have only second-order impacts on the sensitivity to higgsinos.

12. Conclusion

The dissertation presents the search for higgsinos using 140 fb^{-1} of proton-proton collisions at center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ at the LHC, collected by the ATLAS detector in 2015–2018. The search targets final states with a high- p_T hadronic jet, large E_T^{miss} , and two low- p_T leptons, which is the expected event topology of higgsino pair production events with the neutral higgsino decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$. The sensitivity to higgsinos has been drastically improved by the development and application of new low- p_T electron and muon track identification algorithms and the introduction of neural-network-based event selection techniques which consider the kinematic dependencies on $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. The dominant 1L + fake lepton track background has been estimated by a data-driven method to reduce MC modeling uncertainties on the fake lepton track. In all Signal Regions, no significant excess of data has been observed.

Exclusion limits on the target higgsino models have been set at 95% confidence level. In the context of the simplified higgsino model with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, higgsino mass of up to 130 GeV has been excluded for target regions of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1\text{--}2 \text{ GeV}$. The limits in terms of higgsino mass have been extended by 40 GeV, compared to the results from the LEP2 experiment. This is the first search at the LHC to probe such mass splitting regions; this search has successfully contributed to covering the “higgsino gap” with the LHC.

13. Contributions to the Level-1 Muon Trigger System in Run 3

The muon trigger system is crucial for probing new physics in the ATLAS experiment; although the search presented in this dissertation does not directly use the muon trigger, it is exploited in many of the efficiency measurements of the objects used in this search, such as the muon and the low- p_T muon track in the muon channel. In addition to the search for higgsinos, significant efforts have been put into leading the development, commissioning, and the operation of the TGC detector and Level-1 muon trigger systems for LHC Run 3. This section briefly summarizes the contributions, primarily made during my Master's program in 2019–2021.

13.1 Run 3 upgrade of the Level-1 muon trigger

As described earlier in Section 2.2.7, the ATLAS Level-1 muon trigger is a hardware-based system, which triggers physics events of interest by identifying muon candidates in the RPC and TGC detectors for barrel and endcap regions, respectively. For LHC Run 3, the Level-1 endcap muon trigger has been significantly upgraded from Run 2; New Small Wheel (NSW) [177] detector and other inner muon detectors have been introduced to reduce fake muon trigger signals originating from protons emerging from the beam pipe and toroid magnets, as illustrated in Fig. 13.1. By taking the coincidence between the TGC and the inner muon detectors, reduction of fake muon trigger signals has been achieved as shown in Fig. 13.2 [178].

Since the inputs to the trigger logic have largely increased due to the introduction of new detectors, the backend trigger logic boards had to be newly designed. Therefore, New Sector Logic (New SL) boards [179], capable of processing the endcap muon trigger using the inputs from TGC and NSW detectors, have been developed. The surrounding systems, which for example handle clock signal distribution, trigger readout, and trigger output processing, have also been developed accordingly.

13.2 Realization of integrated control

In the summer of 2019, the development of the Run 3 Level-1 muon trigger was still at its preparatory stage, where tests of the new electronics, including the New SL boards, were still carried out at single board level. The implementation of the new electronics and their corresponding software applications to the ATLAS control system was of utmost priority

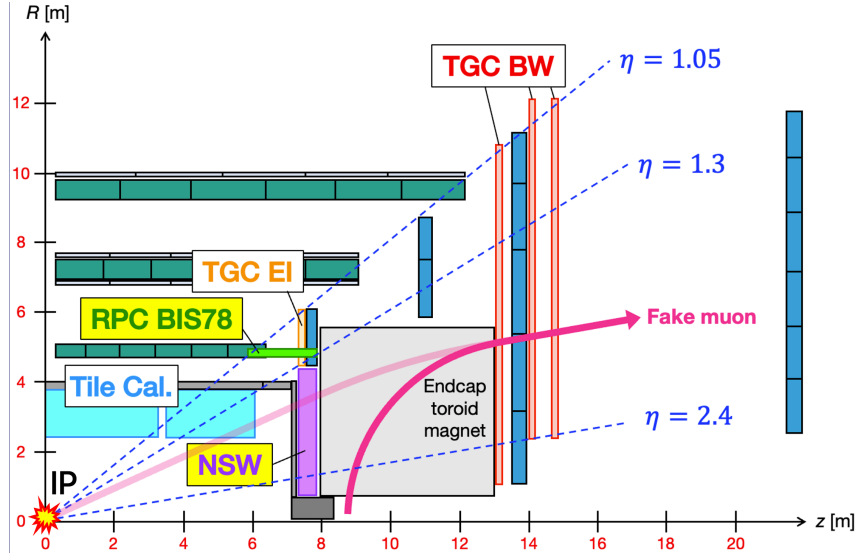
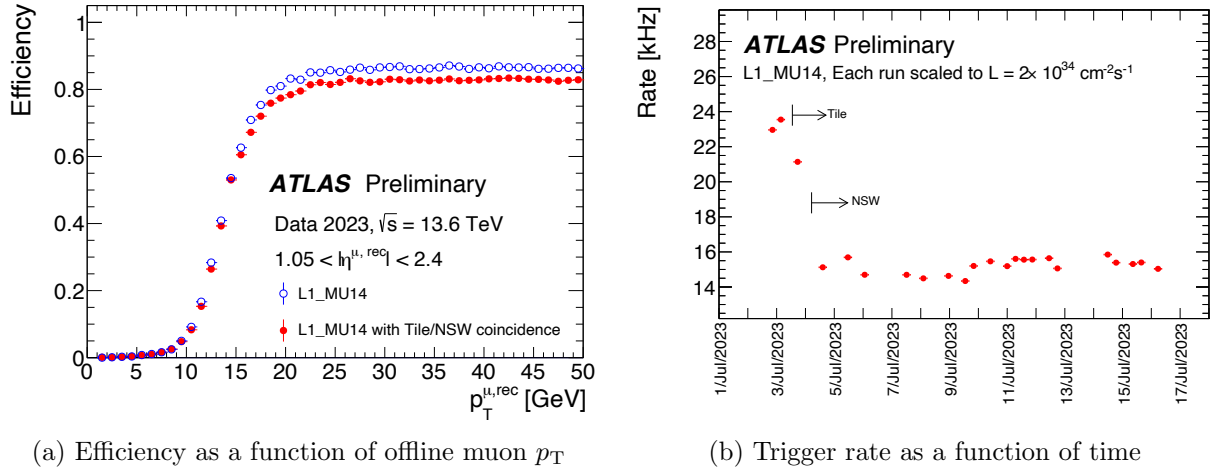


Figure 13.1: A schematic illustration of detectors involved in the Run 3 Level-1 endcap muon trigger and the fake muon trigger signals.



(a) Efficiency as a function of offline muon p_T

(b) Trigger rate as a function of time

Figure 13.2: The performance of the Level-1 muon trigger in 2023 [178], before and after the enablement of the coincidence between TGC and inner detectors: Tile and NSW. Enabling the coincidence has reduced the trigger rate by 8 kHz, while the drop of plateau efficiency has been kept to approximately 4%.

to proceed with further commissioning of the system.

This has been achieved by redesigning and developing the TDAQ software and database necessary to systematically control the whole system. The Run 3 Level-1 muon trigger system has been successfully synchronized to the legacy Run 2 TGC frontend system by scrutinization of the initialization procedures of each electronic device and the communication procedures of each optical link between the electronics. Furthermore, the robustness of the system has been enhanced by the implementation of monitoring functionalities of the new electronics, which are capable of detecting possible errors and hardware failures. The softwares and functions described here are currently in use in the ongoing Run 3 data-taking.

13.3 Development of a new software-based readout system

For offline validation and performance evaluation of the Run 3 Level-1 endcap muon trigger algorithm, the trigger logic input and output data must be read out. This was originally done by a hardware-based system in Run 2, however, a new software-based readout system called Software-based Readout Driver (SROD) [180], has been developed for Run 3 to improve flexibility and to cope with large increase in trigger input data. Stable trigger readout has been achieved at 100 kHz by scrutinization and modification of the event-building software and evaluating its performance.

Fig. 13.3 shows an overview of the SROD and its software structure. The SROD is designed to run on a commercially available high-performance servers. A single SROD receives trigger inputs and outputs from 12 New SL boards via TCP/IP protocol. It adopts a multi-process architecture to collect data and build the event data in parallel. The “EventBuilder” application is responsible for formatting the final event data, which is sent out the ATLAS Readout System (ROS). Therefore, the EventBuilder application has the heaviest load, and its performance determines the performance of the SROD system. For stable operation at the nominal Level-1 trigger rate of 100 kHz, the event-building must be processed within 10 μ s on average.

The processing speed of the EventBuilder application has been improved by countless code optimizations including the reduction of certain variable types and the use of array of function pointers. As a result, the performance of the SROD reached well beyond that was expected to be required for Run 3 as shown in Fig. 13.4. The performances shown in these figures have been evaluated in 2021, however, further modifications have been carried out before the start of Run 3 in 2022.

13.4 Commissioning and stable operation

Significant contributions have been made not only by the developments of the softwares and systems, but also by means of commissioning and stable operation. Contributions to the commissioning include the one with ATLAS central trigger system immediately before Run 3; the timing of the endcap muon trigger signals, crucial for data-taking, has been successfully adjusted by analyzing signals from cosmic muon runs and initial

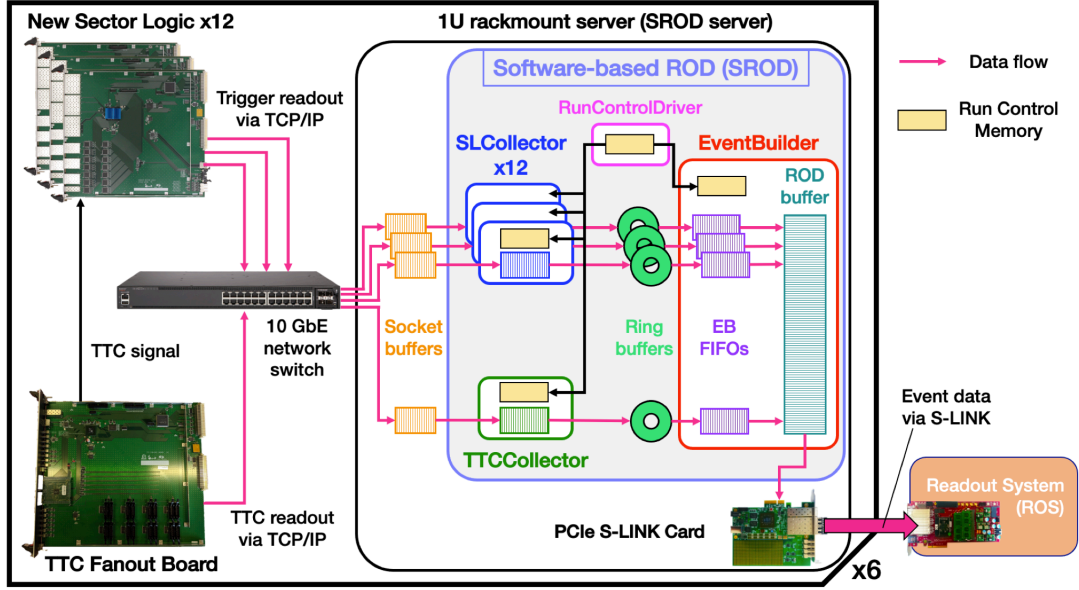


Figure 13.3: Overview of the SROD system used in the ATLAS Level-1 endcap muon trigger in Run 3 [180]. The software structure of the SROD is shown in detail.

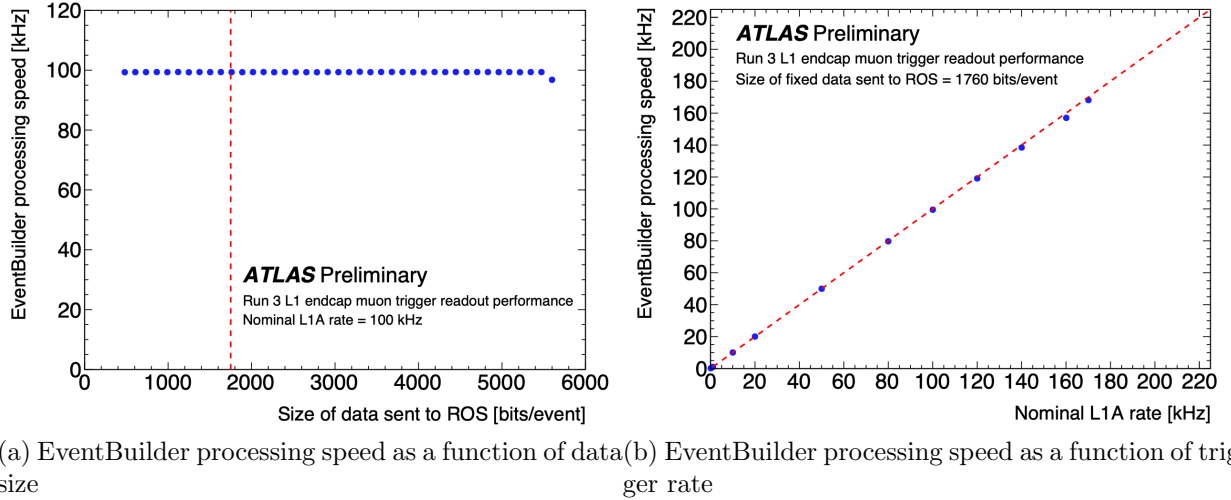


Figure 13.4: The performance of EventBuilder application in the SROD, as a function of data size and trigger rate [180]. At the nominal trigger rate of 100 kHz, the SROD system can handle up to 4800 bits per event, which is more than 2.5 times larger than the expected size of 1750 bits in Run 3. For a fixed data size of 1760 bits per event, the SROD system can run stably up to the speed of 170 kHz, which is well beyond the nominal trigger rate.

proton-proton collision runs. Contributions to the stable operation of the system include,

- Handling unexpected errors and promptly recovering the system during physics data-taking,
- Supporting team members to deal with such problems on-site at CERN and remotely from Tokyo,

which have been done countless times in 2022–2023.

13.5 Summary

Through the developments and implementations of the new Level-1 muon trigger system, its tests with surrounding systems and adjustment of signals have been realized in an opportune manner. Consequently, the Level-1 muon trigger system has successfully started its operation at the start of LHC Run 3, realizing stable data-taking necessary for further physics analysis.

Acknowledgements

I am profoundly grateful to those who have supported me to make this dissertation. First and foremost, I would like to express my deepest gratitude to my supervisor, Prof. Yasuyuki Okumura, for everything that he has done to support this research and my life as a graduate student. The past five and a half years would not have been as successful and fruitful without his encouragement. My sincere appreciation also goes to Prof. Shion Chen, who has supervised this analysis as the leader of ATLAS Japan SUSY group and a former member of Tokyo ICEPP. I would also like to convey my gratitude to Prof. Tomoyuki Saito for reviewing this analysis from its feasibility stage and also proofreading this dissertation. I would like to thank Prof. Masaya Ishino, Prof. Tatsuya Masubuchi, and Prof. Takuya Nobe for providing support and feedbacks in ATLAS Tokyo MIYOLab¹ meetings.

I am grateful to all the members of ATLAS SUSY group. Dr. Jeff Shahinian and Dr. Michael Holzbock have given numerous feedbacks and technical support to this research as analysis contacts. Prof. Ira Joseph Kroll and Prof. Tommaso Lari have given keen insights to this research in weekly analysis meetings. Dr. Javier Montejo Berlingen, Dr. Sara Alderweireldt, Dr. Federico Meloni, and Prof. Iacopo Vivarelli have supported this analysis as the leaders of the SUSY group, and Dr. Sonia Carra and Dr. Daniela Kock have supported this analysis as the leaders of SUSY Electroweak subgroup. Prof. Hideyuki Oide, Dr. Guglielmo Frattari, and Dr. Otilia Anamaria Ducu have reviewed this analysis for unblinding.

I would also like to thank all staff members and students of Tokyo ICEPP and ATLAS Japan group for providing support. Prof. Shoji Asai, Prof. Ryu Sawada, and Prof. Masahiko Saito have provided feedbacks and technical support to kick-off the study of the low- p_T electron track tagger and higgsino search. Prof. Junichi Tanaka and Prof. Yuji Enari have given helpful ideas and feedbacks in ICEPP analysis meetings. Dr. Hiroaki Hibi has developed the low- p_T muon track tagger and parts of the analysis software framework used in this research. Dr. Yuya Mino has provided a lot of technical support in analysis softwares and engaged in numerous physics discussions. I would also like to express my gratitude to the secretaries of ICEPP for their enormous support, facilitating this research.

Last but not least, I would like to thank my family, partner, and friends who have always been there for me.

¹Abbreviation for “Masaya Ishino – Yasuyuki Okumura Lab”.

A. Signal MC Samples

Table A.1 shows the leptonic branching ratios of the $\tilde{\chi}_2^0$ for each $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ (excluding the decays to taus), which is used to calculate the production cross sections of the signal samples. The values have been taken from Ref. [92].

Table A.1: Leptonic branching ratios of the $\tilde{\chi}_2^0$ for each $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$.

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]	$\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 e^+ e^-)$	$\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \mu^+ \mu^-)$	Total leptonic BR
1	0.05292	0.04979	0.10271
1.5	0.05112	0.04981	0.10093
2	0.05087	0.04881	0.09968
3	0.05016	0.04924	0.09940
4	0.04730	0.04713	0.09443
5	0.04714	0.04681	0.09395

The full list of MC samples for the signal mass grid are shown in Tables A.2, A.3 and A.4 for $\tilde{\chi}_1^- \tilde{\chi}_2^0$, $\tilde{\chi}_1^+ \tilde{\chi}_2^0$, and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ processes respectively.

Table A.2: List of MC samples for the $\tilde{\chi}_1^- \tilde{\chi}_2^0$ process. The table lists the process, the masses of the higgsinos, the inclusive cross section (including the leptonic BR and the correction with the $\frac{\sigma(>1 \text{ jet})}{\sigma(>0 \text{ jet})}$ factor, as addressed in Section 3.3.1) and its relative uncertainty, the 1J/0J factor, the generator filter efficiency, and the number of generated events.

Process	$m(\tilde{\chi}_2^0)$ [GeV]	$m(\tilde{\chi}_1^\pm)$ [GeV]	$m(\tilde{\chi}_1^0)$ [GeV]	$\sigma_{\text{inc}} [10^{-2} \text{ pb}]$	Rel. unc. [%]	$\frac{\sigma(>1 \text{ jet})}{\sigma(>0 \text{ jet})}$	Filter efficiency	nEvents
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	86	85.5	85	7.9704	4.3398	0.2002	0.1108	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	86.5	85.75	85	7.6983	4.3434	0.2001	0.2034	170k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	87	86	85	7.4350	4.3472	0.1991	0.3094	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	88	86.5	85	7.3373	4.3556	0.2037	0.4921	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	89	87	85	6.6986	4.3649	0.2024	0.5995	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	90	87.5	85	6.5511	4.3714	0.2056	0.6211	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	101	100.5	100	4.7461	4.5057	0.2210	0.1085	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	101.5	100.75	100	4.5618	4.5059	0.2192	0.2017	175k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	102	101	100	4.4561	4.5107	0.2199	0.3140	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	103	101.5	100	4.3400	4.5226	0.2208	0.5001	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	104	102	100	4.0660	4.5314	0.2239	0.6149	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	105	102.5	100	3.9086	4.5406	0.2223	0.6365	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	126	125.5	125	2.3264	4.7880	0.2487	0.1013	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	126.5	125.75	125	2.2432	4.7916	0.2468	0.1936	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	127	126	125	2.2110	4.7961	0.2491	0.2999	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	128	126.5	125	2.1680	4.8055	0.2504	0.5031	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	129	127	125	2.0262	4.8126	0.2518	0.6261	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	130	127.5	125	1.9575	4.8215	0.2499	0.6497	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	151.5	150.75	150	1.2540	5.0670	0.2715	0.1782	210k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	152	151	150	1.2235	5.0711	0.2707	0.2966	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	153	151.5	150	1.1978	5.0797	0.2708	0.4952	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	154	152	150	1.1436	5.0847	0.2772	0.6259	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	155	152.5	150	1.0891	5.0957	0.2703	0.6713	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	176.5	175.75	175	0.7494	5.3323	0.2894	0.1753	150k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	177	176	175	0.7287	5.3359	0.2872	0.2841	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	178	176.5	175	0.7239	5.3486	0.2908	0.4862	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	179	177	175	0.6802	5.3567	0.2923	0.6343	130k
$\tilde{\chi}_1^- \tilde{\chi}_2^0$	180	177.5	175	0.6566	5.3595	0.2882	0.6689	130k

Table A.3: List of MC samples for the $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ process. The table lists the process, the masses of the higgsinos, the inclusive cross section (including the leptonic BR and the correction with the 1J/0J factor, as addressed in Section 3.3.1) and its relative uncertainty, the 1J/0J factor, the generator filter efficiency, and the number of generated events.

Process	$m(\tilde{\chi}_2^0)$ [GeV]	$m(\tilde{\chi}_1^\pm)$ [GeV]	$m(\tilde{\chi}_1^0)$ [GeV]	σ_{inc} [10^{-2} pb]	Rel. unc. [%]	$\frac{\sigma(\geq 1 \text{ jet})}{\sigma(\geq 0 \text{ jet})}$	Filter efficiency	nEvents
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	86	85.5	85	12.5852	2.1831	0.2034	0.1133	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	86.5	85.75	85	12.2372	2.1853	0.2045	0.2067	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	87	86	85	11.7919	2.1874	0.2028	0.3196	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	88	86.5	85	11.5266	2.1952	0.2053	0.4952	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	89	87	85	10.5631	2.2007	0.2044	0.5916	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	90	87.5	85	10.2422	2.2057	0.2056	0.6137	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	101	100.5	100	7.6677	2.3126	0.2234	0.1074	165k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	101.5	100.75	100	7.3719	2.3131	0.2215	0.2064	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	102	101	100	7.3678	2.3168	0.2272	0.3178	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	103	101.5	100	6.9744	2.3274	0.2215	0.5087	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	104	102	100	6.4977	2.3353	0.2230	0.6080	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	105	102.5	100	6.3369	2.3442	0.2243	0.6341	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	126	125.5	125	3.9184	2.5854	0.2515	0.1050	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	126.5	125.75	125	3.8004	2.5900	0.2508	0.1936	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	127	126	125	3.7371	2.5925	0.2524	0.3032	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	128	126.5	125	3.6799	2.6022	0.2545	0.4941	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	129	127	125	3.4351	2.6082	0.2553	0.6247	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	130	127.5	125	3.3492	2.6131	0.2555	0.6472	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	151.5	150.75	150	2.2092	2.8630	0.2764	0.1895	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	152	151	150	2.1823	2.8683	0.2789	0.3017	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	153	151.5	150	2.0642	2.8770	0.2692	0.5030	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	154	152	150	1.9731	2.8925	0.2756	0.6302	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	155	152.5	150	1.9612	2.8960	0.2802	0.6636	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	176.5	175.75	175	1.3552	3.1642	0.2920	0.1784	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	177	176	175	1.3388	3.1684	0.2943	0.2997	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	178	176.5	175	1.2989	3.1766	0.2908	0.5004	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	179	177	175	1.2454	3.1859	0.2979	0.6320	130k
$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	180	177.5	175	1.2185	3.1955	0.2974	0.6666	130k

Table A.4: List of MC samples for the $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ process. The table lists the process, the masses of the higgsinos, the inclusive cross section (including the leptonic BR and the correction with the 1J/0J factor, as addressed in Section 3.3.1) and its relative uncertainty, the 1J/0J factor, the generator filter efficiency, and the number of generated events.

Process	$m(\tilde{\chi}_2^0)$ [GeV]	$m(\tilde{\chi}_1^\pm)$ [GeV]	$m(\tilde{\chi}_1^0)$ [GeV]	$\sigma_{\text{inc}} [10^{-2} \text{ pb}]$	Rel. unc. [%]	$\frac{\sigma(\geq 1 \text{ jet})}{\sigma(\geq 0 \text{ jet})}$	Filter efficiency	nEvents
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	86	85.5	85	12.1973	2.6949	0.1957	0.1048	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	86.5	85.75	85	11.9826	2.6969	0.1979	0.1969	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	87	86	85	11.6443	2.6986	0.1971	0.3095	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	88	86.5	85	11.3284	2.7016	0.1968	0.4935	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	89	87	85	10.5080	2.7075	0.1967	0.5835	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	90	87.5	85	10.2560	2.7128	0.1975	0.6060	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	101	100.5	100	7.2123	2.8329	0.2184	0.1010	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	101.5	100.75	100	6.9762	2.8356	0.2170	0.1893	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	102	101	100	6.9046	2.8352	0.2196	0.3032	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	103	101.5	100	6.7946	2.8399	0.2208	0.4852	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	104	102	100	6.3230	2.8487	0.2205	0.6051	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	105	102.5	100	6.1614	2.8552	0.2200	0.6176	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	126	125.5	125	3.5227	3.1148	0.2464	0.0973	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	126.5	125.75	125	3.4413	3.1179	0.2468	0.1860	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	127	126	125	3.3865	3.1202	0.2478	0.2909	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	128	126.5	125	3.2989	3.1253	0.2456	0.4893	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	129	127	125	3.0649	3.1310	0.2438	0.6174	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	130	127.5	125	3.0376	3.1366	0.2465	0.6387	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	151.5	150.75	150	1.9076	3.3957	0.2681	0.1847	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	152	151	150	1.8895	3.3986	0.2705	0.2831	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	153	151.5	150	1.8715	3.4042	0.2720	0.4973	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	154	152	150	1.7539	3.4100	0.2717	0.6210	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	155	152.5	150	1.7464	3.4171	0.2753	0.6448	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	176.5	175.75	175	1.1653	3.6821	0.2897	0.1744	175k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	177	176	175	1.1368	3.6849	0.2876	0.2835	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	178	176.5	175	1.1323	3.6905	0.2904	0.4971	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	179	177	175	1.0484	3.6962	0.2860	0.6328	130k
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	180	177.5	175	1.0531	3.7020	0.2918	0.6618	130k

B. Details of Low- p_T Lepton Track Identification

B.1 Input variables of LPET ID DNN

This section summarizes the data/MC distributions of the inputs used for the LPET ID DNN. Since it is difficult to extract only real electron tracks in data, the distributions for all tracks are presented for reference. In particular, for events passing the event preselection criteria in Table 6.1, distributions for all tracks passing the selection criteria in Table 6.2 with flipped charge requirement (same-sign, SS) and higher track p_T requirement of $p_T > 1$ GeV are shown. The higher track p_T requirement is imposed to briefly reduce background tracks. For MC, all background samples listed in Table 3.3 have been used.

Figures B.1–B.4, Figure B.5 and Figure B.6 show the distributions of track, TRT, and calo inputs used for the LPET ID DNN, respectively. There are some variables with poor data/MC modelling (e.g. eProbabilityComb and TRTHighThresholdHits), which are thought to be the main cause of the small scale factors of LPET ID WP, shown in Figure 5.19. However, these variables have high importance in the identification of electron tracks, hence have been kept as LPET ID inputs.

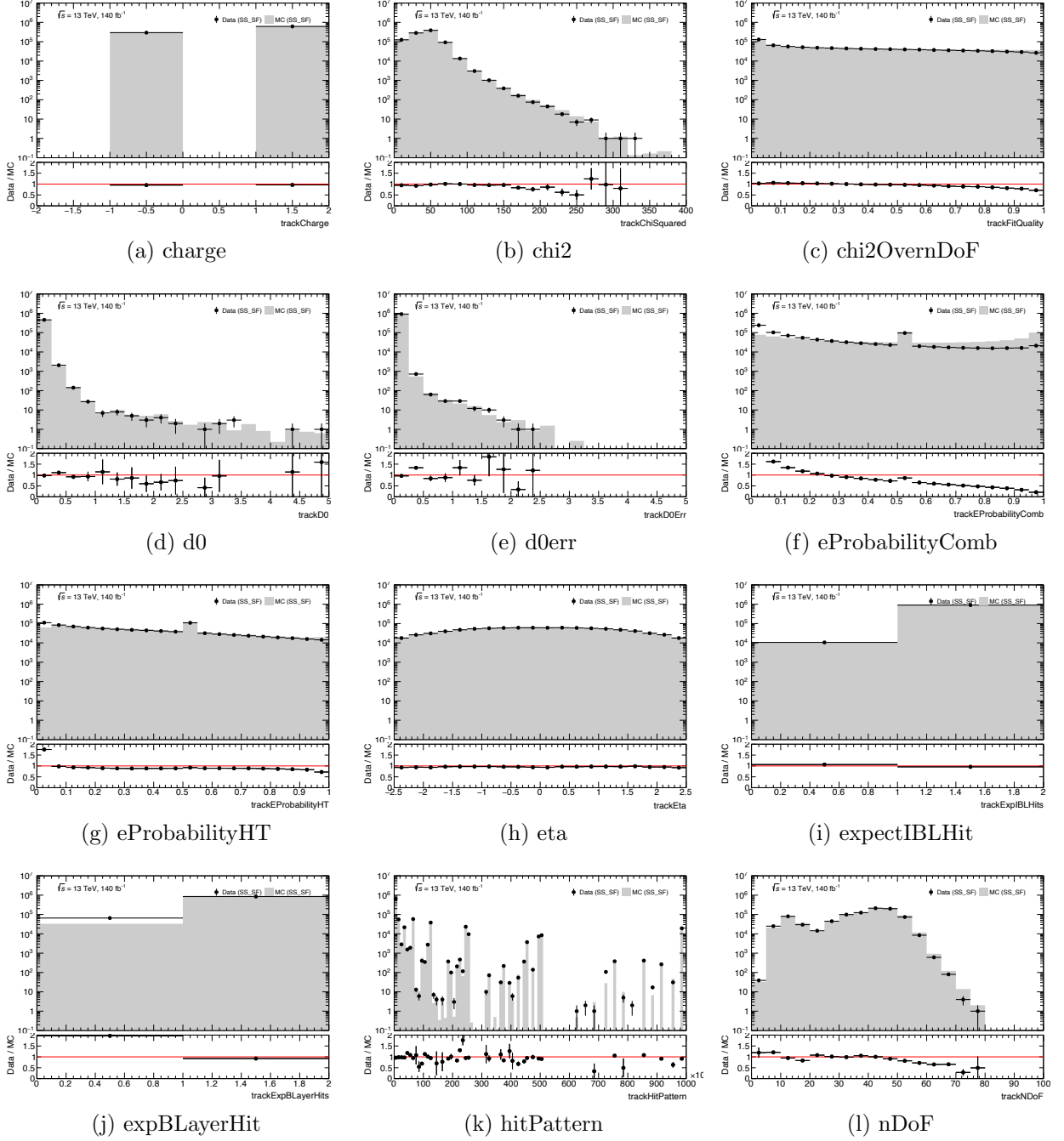
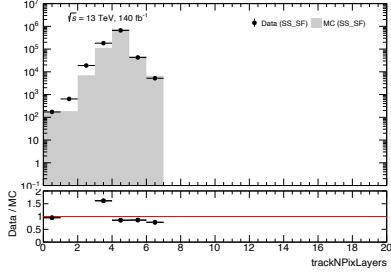
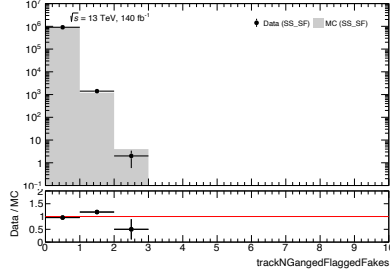


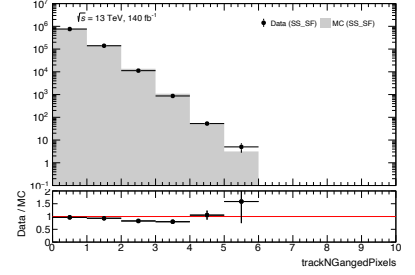
Figure B.1: SS track data/MC of track inputs used for LPET ID DNN (part 1).



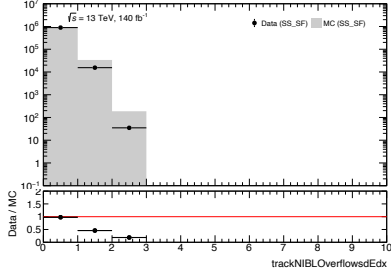
(a) numOfContribPixelLayers



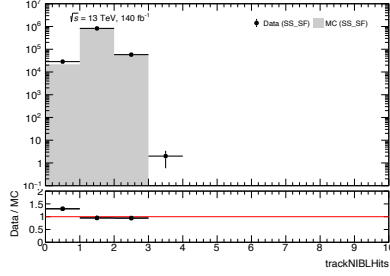
(b) numOfGangedFlaggedFakes



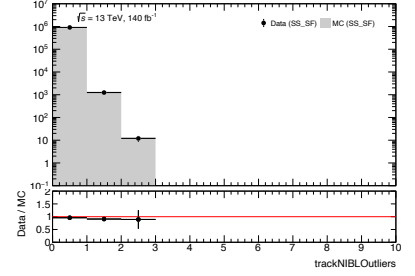
(c) numOfGangedPixels



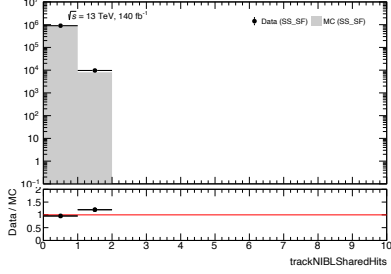
(d) numOfIBLOverflowsEdx



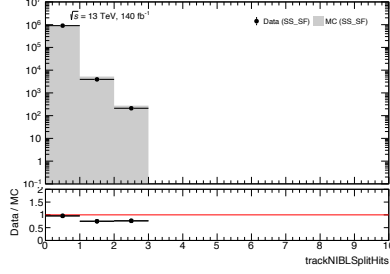
(e) numOfIBLHits



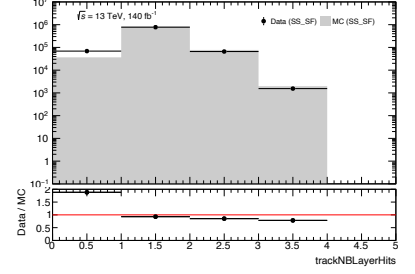
(f) numOfIBLOutliers



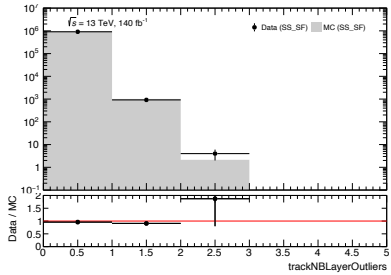
(g) numOfIBLSharedHits



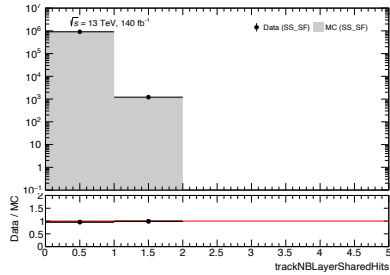
(h) numOfIBLSplitHits



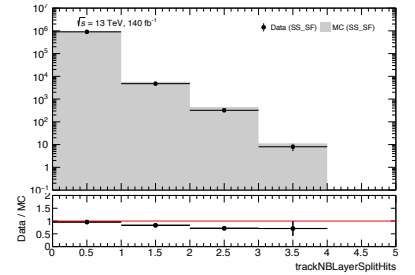
(i) numOfBLayerHits



(j) numOfBLayerOutliers

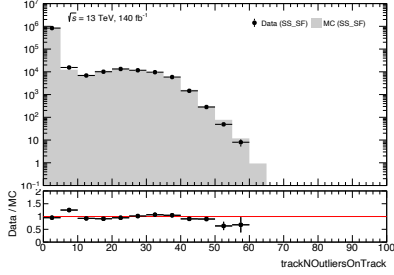


(k) numOfBLayerSharedHits

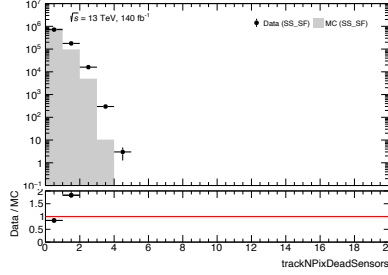


(l) numOfBLayerSplitHits

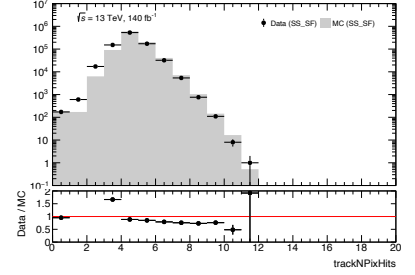
Figure B.2: SS track data/MC of track inputs used for LPET ID DNN (part 2).



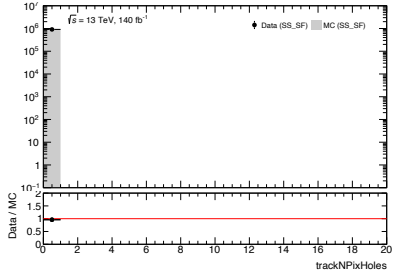
(a) numOfOutliersOnTrack



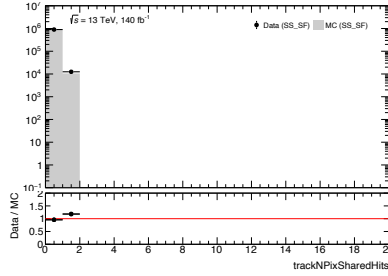
(b) numOfPixelDeadSensors



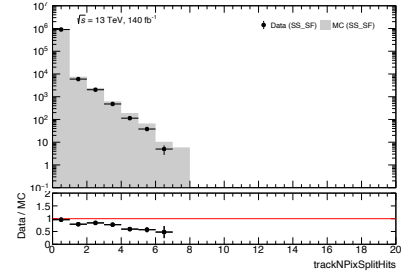
(c) numOfPixelHits



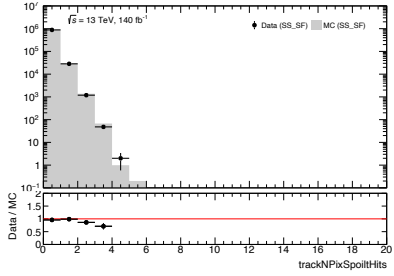
(d) numOfPixelHoles



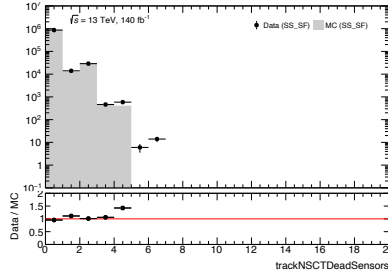
(e) numOfPixelSharedHits



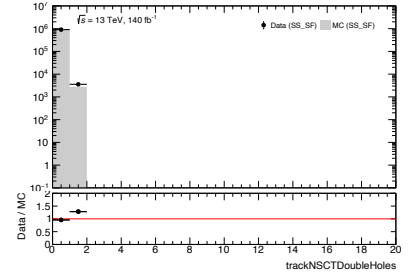
(f) numOfPixelSplitHits



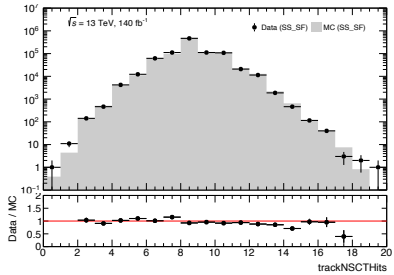
(g) numOfPixelSpoiltHits



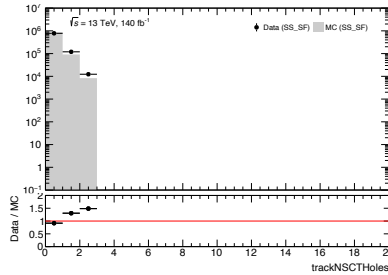
(h) numOfSCTDeadSensors



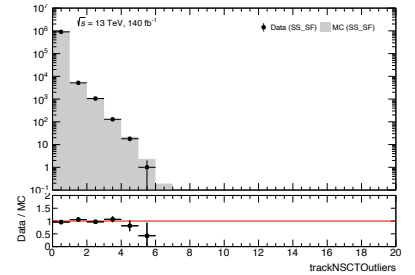
(i) numOfSCTDoubleHoles



(j) numOfSCTHits



(k) numOfSCTHoles



(l) numOfSCTOutliers

Figure B.3: SS track data/MC of track inputs used for LPET ID DNN (part 3).

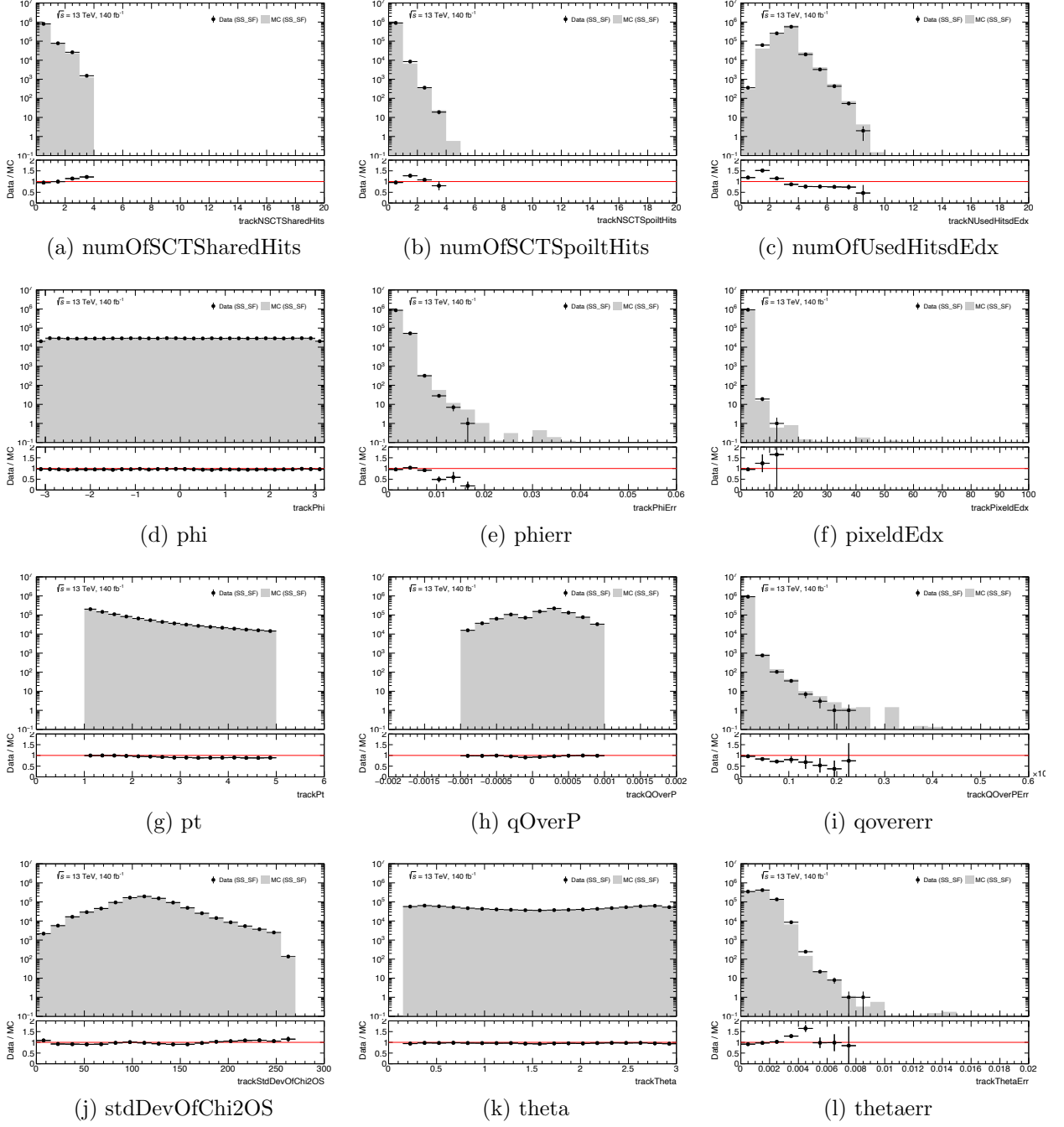


Figure B.4: SS track data/MC of track inputs used for LPET ID DNN (part 4).

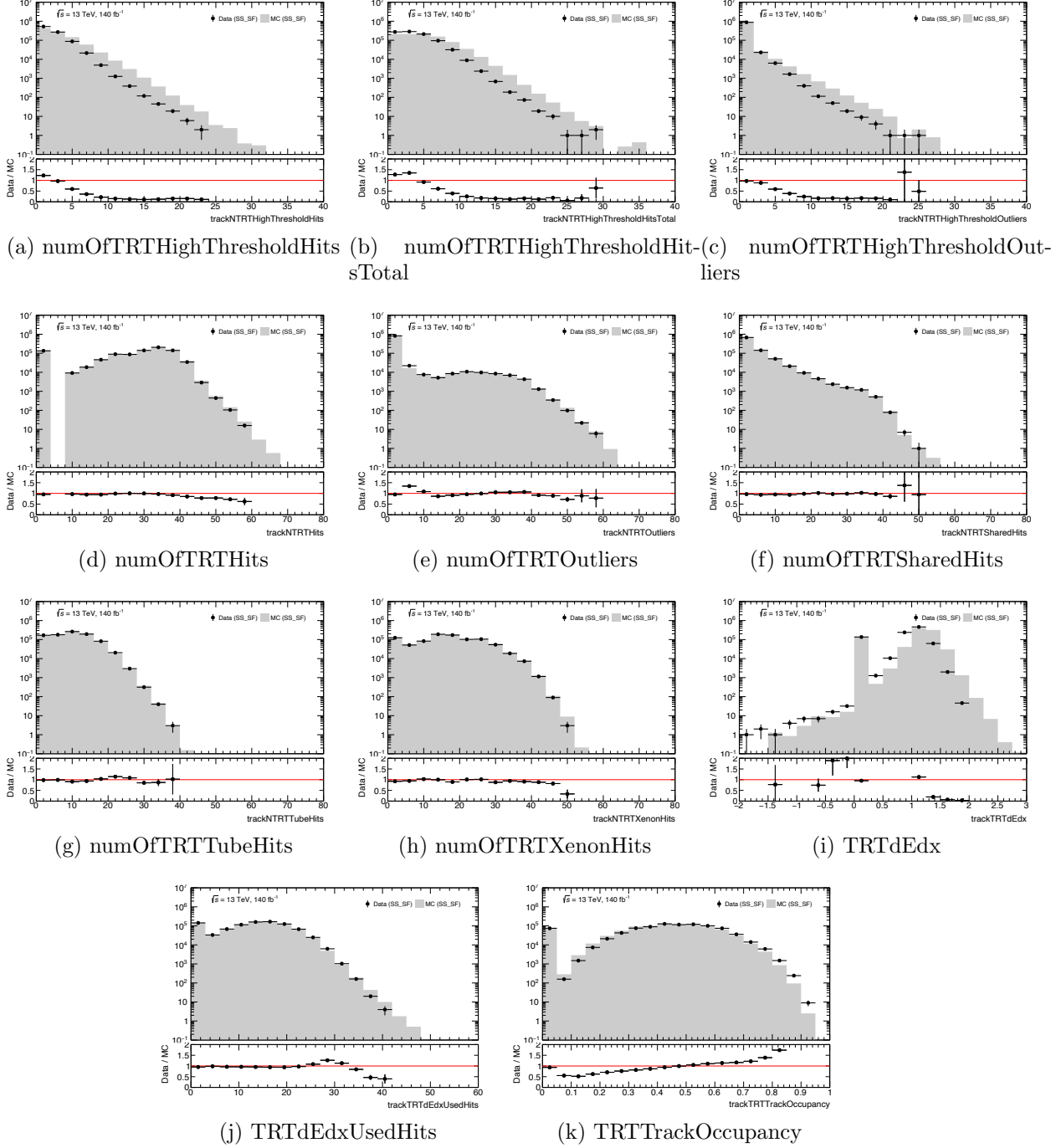


Figure B.5: SS track data/MC of TRT inputs used for LPET ID DNN.

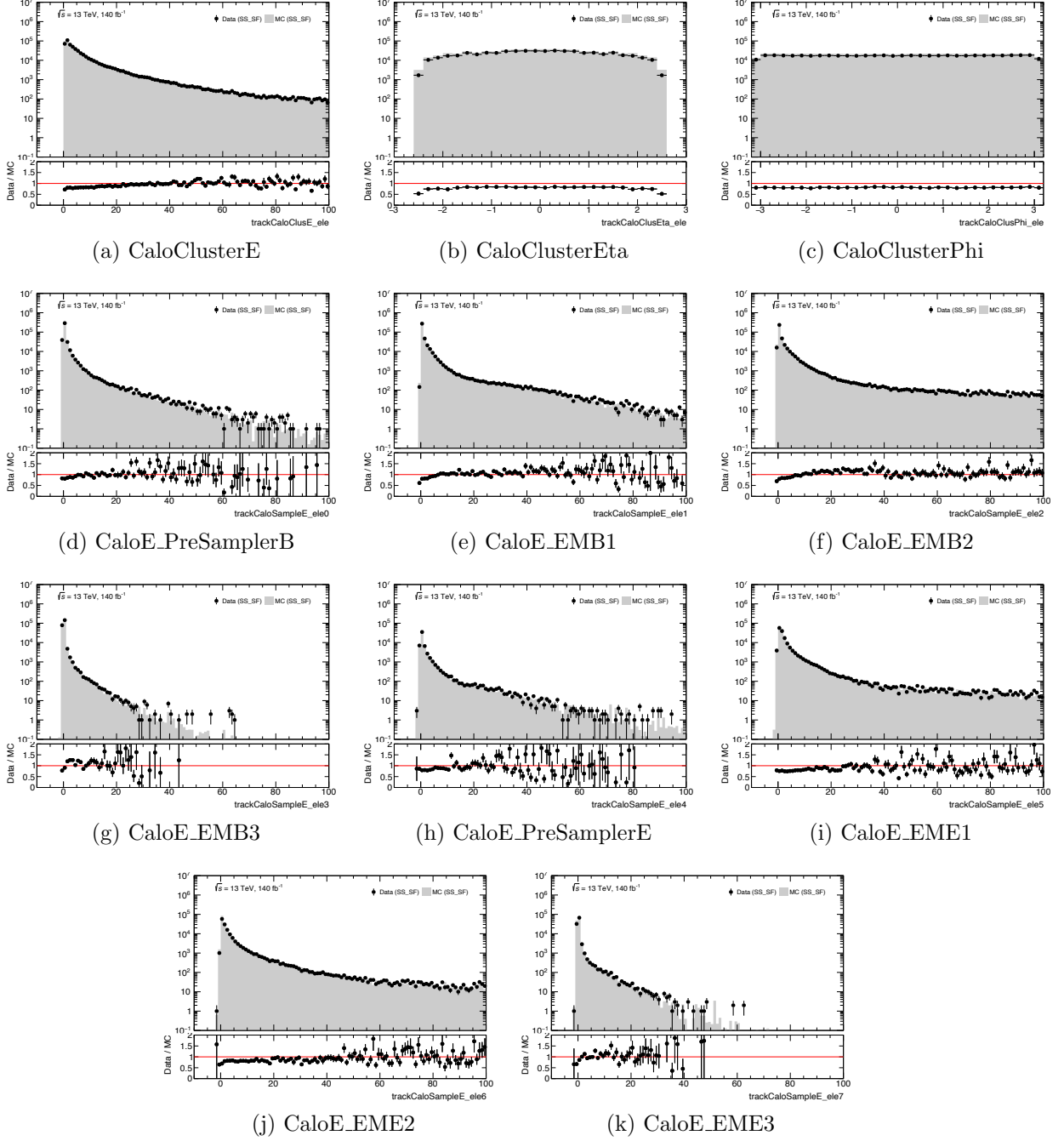


Figure B.6: SS track data/MC of calo inputs used for LPET ID DNN. For each calorimeter layer, the original raw energy distribution is shown, instead of the energy ratio and validity variables used as inputs.

B.2 Performance measurement and calibration

This section describes the samples and event selection criteria used for the performance measurement and calibration of LPET ID. Target events are $Z \rightarrow ee\gamma$ processes as described in Section 5.1.3.

B.2.1 MC samples

Table B.1 summarizes the MC samples used for the performance measurement. All samples have been simulated with GEANT4 [141], and simulation of the effects of pileup is performed as described in Section 3.3.3.

Table B.1: List of background MC samples used for the performance measurement of LPET ID.

Physics process	Generator	Parton shower	Tune
$Z \rightarrow ee\gamma$	SHERPA 2.2.11	SHERPA	SHERPA
$Z \rightarrow ee$	SHERPA 2.2.11	SHERPA	SHERPA
Drell-Yan ee	POWHEG-BOX v1	PYTHIA v8.186	AZNLO CTEQ6L1

B.2.2 Event and track selection criteria

The performance measurement of LPET ID targets $Z \rightarrow ee\gamma$ processes as described in Section 5.1.3. Table B.2 shows the event selection criteria. Selections have been optimized to suppress $Z \rightarrow ee$ background events as much as possible, without discarding too much signal $Z \rightarrow ee\gamma$ events.

Each of the selected events by the above criteria usually have multiple track candidates surrounding the photon, most of them being background hadronic or fake tracks. These background tracks must be reduced as much as possible to estimate the number of signal electron tracks coming from $Z \rightarrow ee\gamma$ processes. Table B.3 summarizes the track preselection criteria for reducing the background tracks. The selection criteria have been optimized to select signal electron tracks and suppress other background tracks. All tracks passing these criteria are used in the performance measurement of LPET ID.

B.2.3 $dR(\text{trk}, \gamma)$ distributions for each track p_T bin

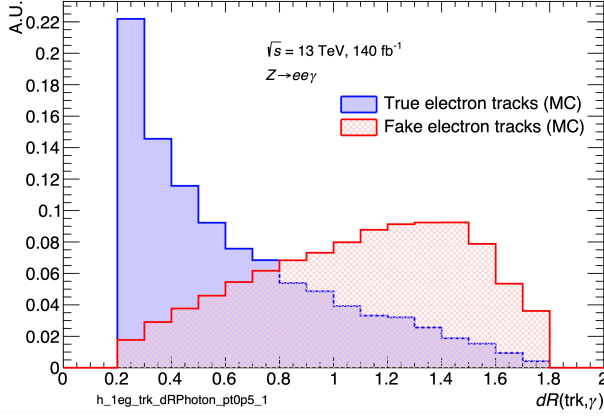
Figures in this section show the $dR(\text{trk}, \gamma)$ distributions used in the LPET ID performance measurement for each track p_T bin. Figure B.7 shows the MC shape distributions used for the fits. Figure B.8 shows the post-fit distributions for WP pass tracks. Figure B.9 shows the post-fit distributions for WP fail tracks.

B.2.4 Efficiency and scale factors for fake electron tracks

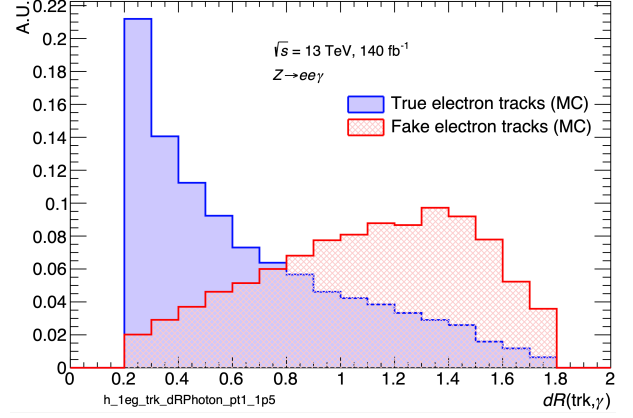
Although the efficiency and scale factors for fake electron tracks are not used in the analysis, it is worthwhile to mention them here. Efficiency for fake electron tracks could also be obtained as done for true electron tracks, by simply counting the number of fake electron tracks passing and failing the LPET ID WP from the post-fit $dR(\text{trk}, \gamma)$

Table B.2: Event selection applied to events used for LPET ID performance measurement.

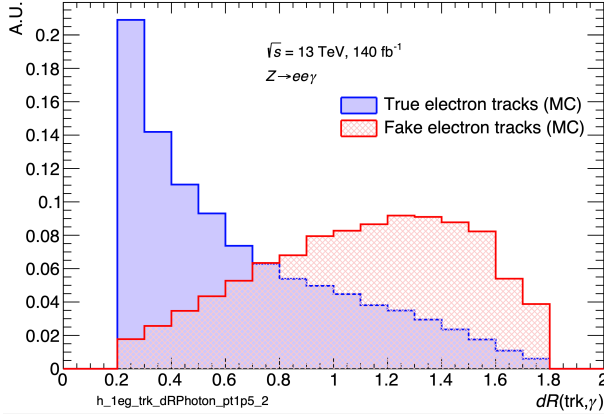
Variable	Requirement
Trigger	Single electron trigger
Number of b -jets	$= 0$
E_T^{miss} [GeV]	< 50
Leading jet cleaning WP	<i>Tight</i>
Number of signal electron	$= 1$
Electron p_T [GeV]	$[30, 60]$
Electron $ z_0 $ [mm]	< 0.1
Electron $ d_0 $ [mm]	< 0.1
Electron $ d_0/\sigma(d_0) $	< 3
Electron isolation WP	<i>IsoLoose_VarRad</i>
Electron AmbiguityType	$= 0$
Electron AddAmbiguity	≤ 0
Number of baseline photon	$= 1$
Photon p_T [GeV]	$[30, 55]$
Photon isolation WP	<i>IsoFixedCutLoose</i>
Photon conversion veto	Enabled
$dR(e, \gamma)$	< 3.5
$d\eta(e, \gamma)$	< 1.7
$\Delta\phi(e, \gamma)$	> 2.5
$m(e, \gamma)$ [GeV]	$[76, 94]$



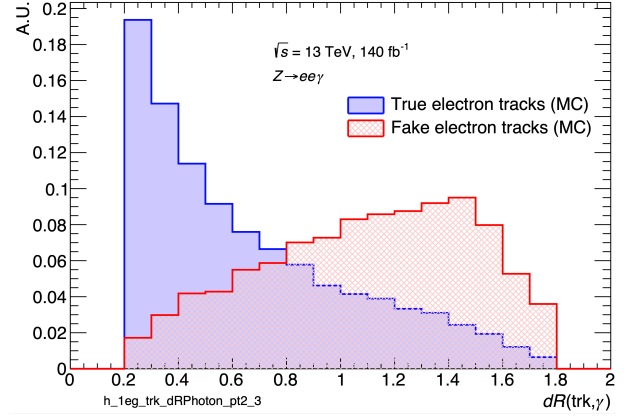
(a) Track $p_T = 0.5-1$ GeV



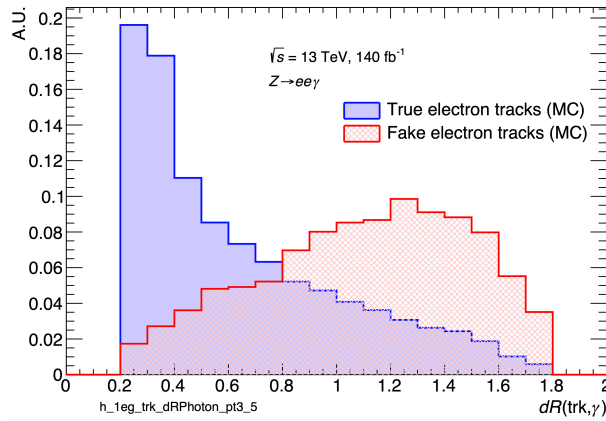
(b) Track $p_T = 1-1.5$ GeV



(c) Track $p_T = 1.5-2$ GeV



(d) Track $p_T = 2-3$ GeV



(e) Track $p_T = 3-5$ GeV

Figure B.7: Normalized distributions of $dR(\text{trk}, \gamma)$ for true and fake electron tracks for each track p_T bin. These MC shapes are used as templates for fitting the data for both WP pass and fail tracks.

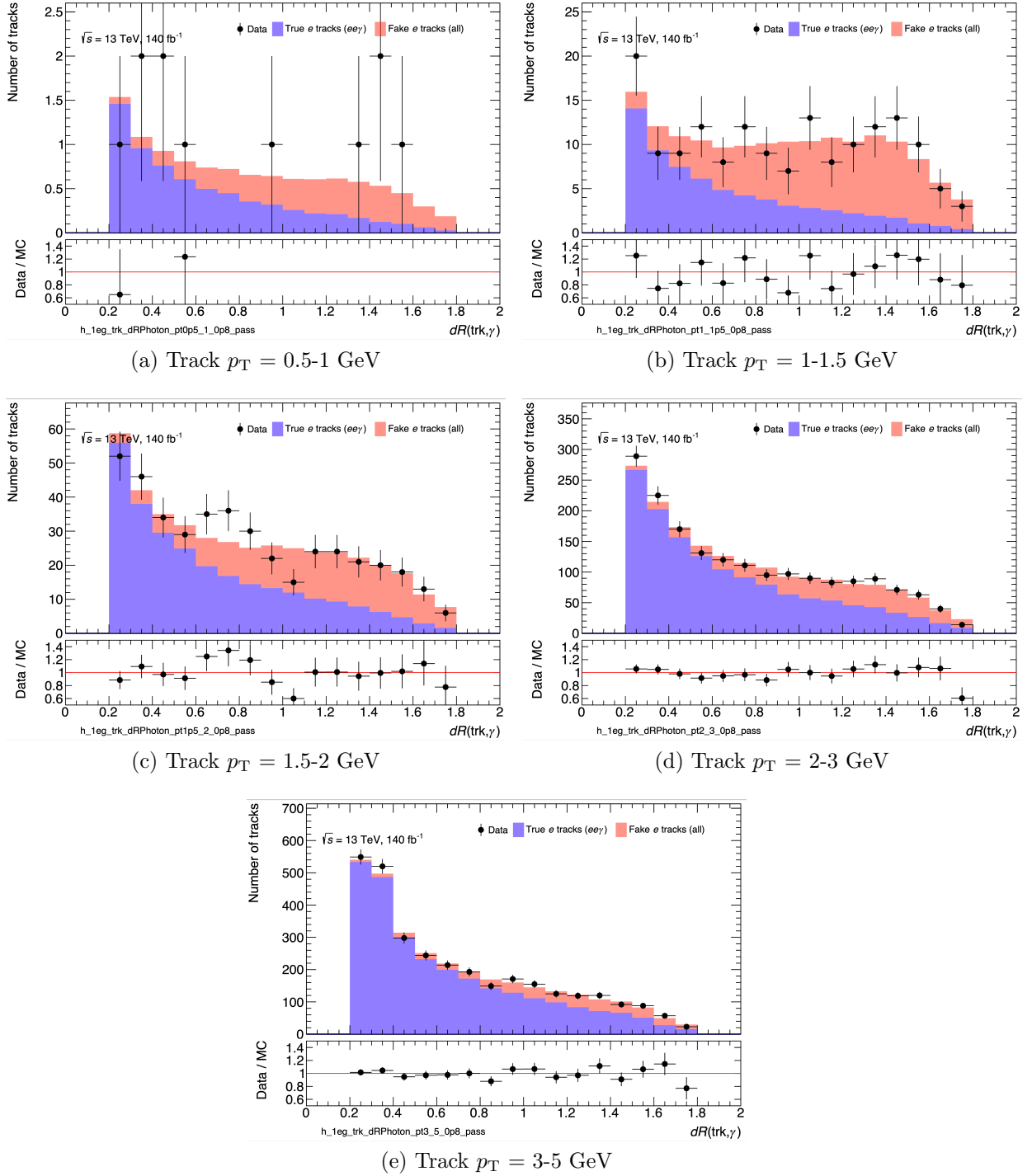
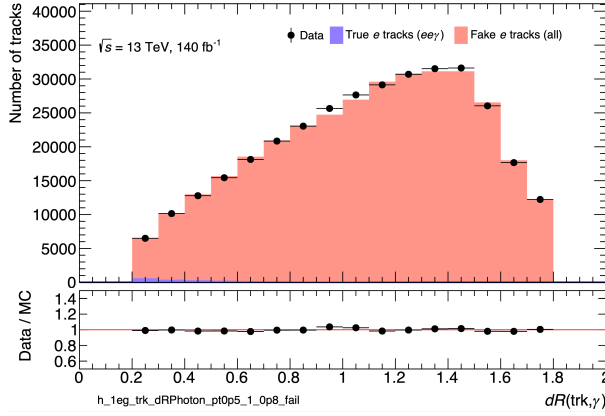
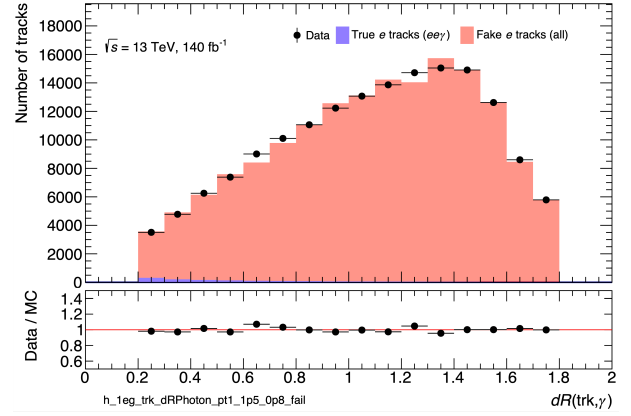


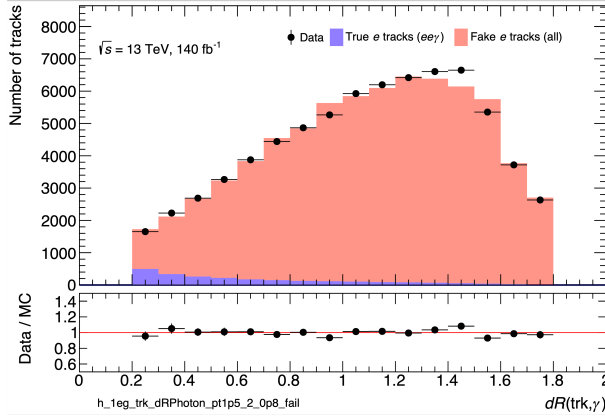
Figure B.8: Post-fit distributions of $dR(\text{trk}, \gamma)$ for WP pass tracks for each track p_T bin. The blue and red histograms represent the fitted distributions of true and fake electron tracks, respectively.



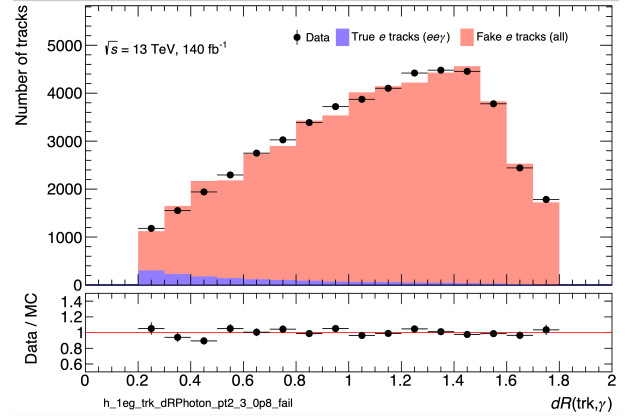
(a) Track $p_T = 0.5-1$ GeV



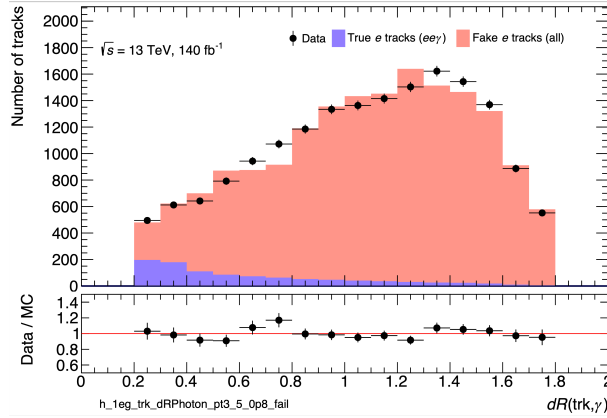
(b) Track $p_T = 1-1.5$ GeV



(c) Track $p_T = 1.5-2$ GeV



(d) Track $p_T = 2-3$ GeV



(e) Track $p_T = 3-5$ GeV

Figure B.9: Post-fit distributions of $dR(\text{trk}, \gamma)$ for WP fail tracks for each track p_T bin. The blue and red histograms represent the fitted distributions of true and fake electron tracks, respectively.

Table B.3: Track preselection applied to low- p_T electron candidate tracks used for LPET ID performance measurement.

Variable	Requirements
Quality WP	<i>Tight Primary</i>
Charge	Opposite of electron charge
p_T [GeV]	[0.5, 5]
$ \eta $	< 2.5
$ z_0 $ [mm]	< 0.25
$ d_0 $ [mm]	< 0.2
Isolation WP	$p_T \text{Varcone30}/p_T = 0$
$dR(\text{trk}, e)$	[1.6, 3.5]
$d\eta(\text{trk}, e)$	< 2.0
$\Delta\phi(\text{trk}, e)$	> 1.6
$dR(\text{trk}, \gamma)$	[0.2, 1.8]
$d\eta(\text{trk}, \gamma)$	< 1.5
$\Delta\phi(\text{trk}, \gamma)$	< 1.6
$m(\text{trk}, \gamma)$ [GeV]	[1, 25]

distribution. Figure B.10 shows the LPET ID efficiency for true and fake electron tracks for both $Z \rightarrow ee\gamma$ data and MC. The efficiency for fake electron tracks have a relation between data and MC similar to the true electron tracks; the efficiency for data is lower compared to MC. Figure B.11 shows the scale factors for true and electron tracks, obtained by taking the ratios of Figure B.10a and Figure B.10b. The scale factors for fake electron tracks are comparable to those of true electron tracks for $p_T < 2$ GeV, whereas they are relatively smaller for $p_T > 2$ GeV. This indicates that the signal to background ratio of LPET ID is rather higher for data compared to what has been evaluated using MC.

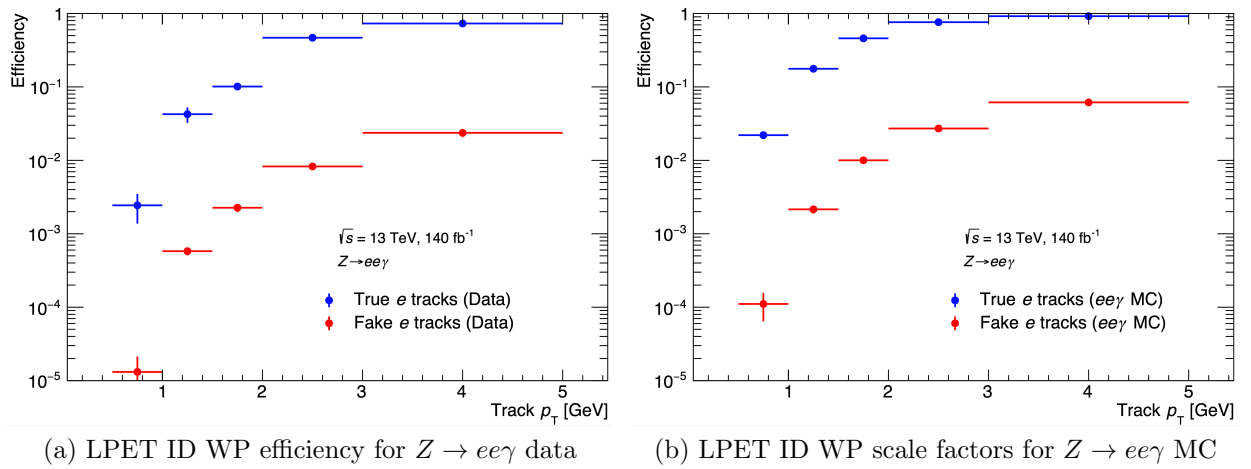


Figure B.10: LPET ID WP efficiency for true and fake electron tracks for $Z \rightarrow ee\gamma$ data and MC.

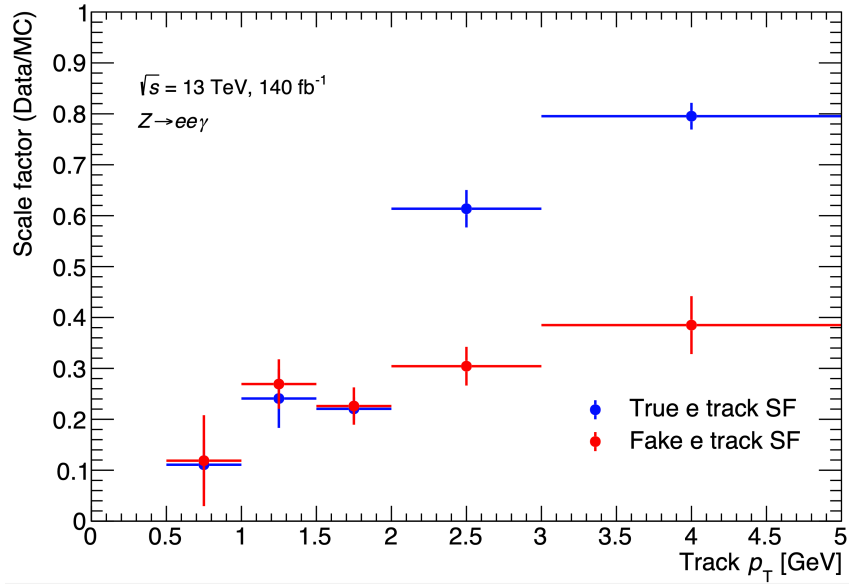
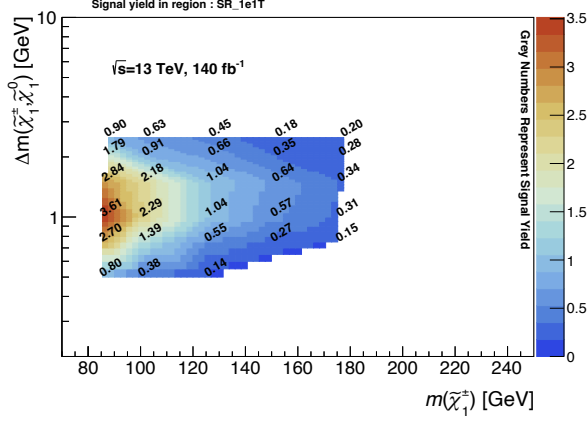


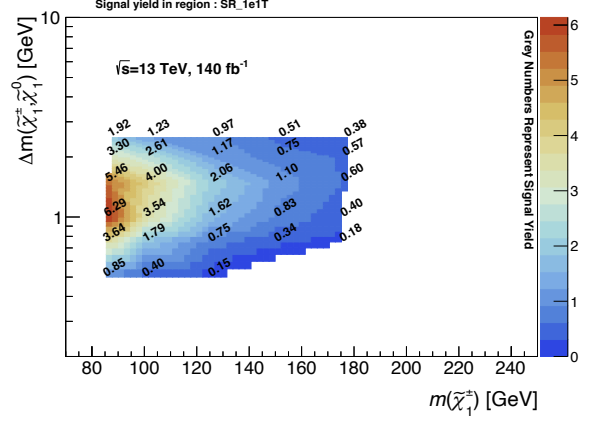
Figure B.11: LPET ID scale factors for true and fake electron tracks.

C. Signal yields

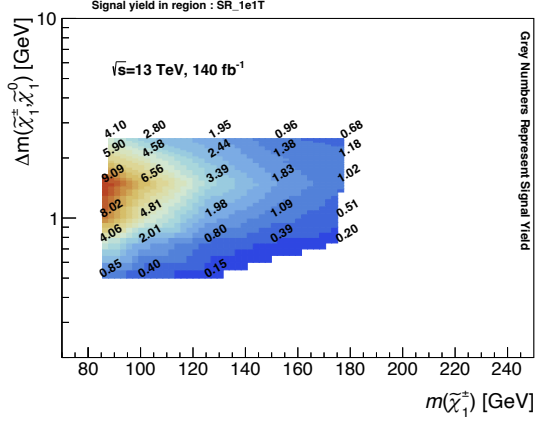
Figure C.1 and Figure C.2 show the expected signal yields in SR for each mass point for the electron and muon channels, respectively.



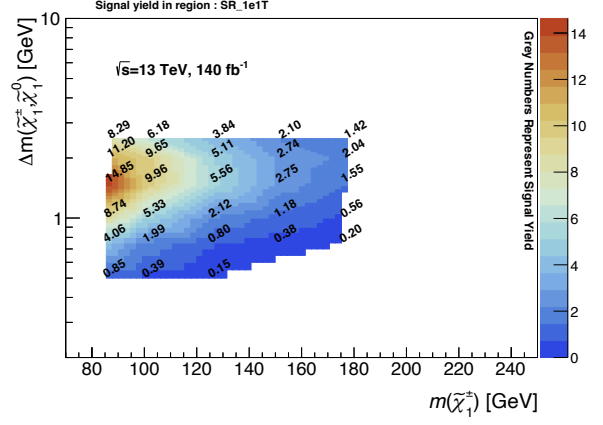
(a) $pNN-\theta = 1 \text{ GeV}$



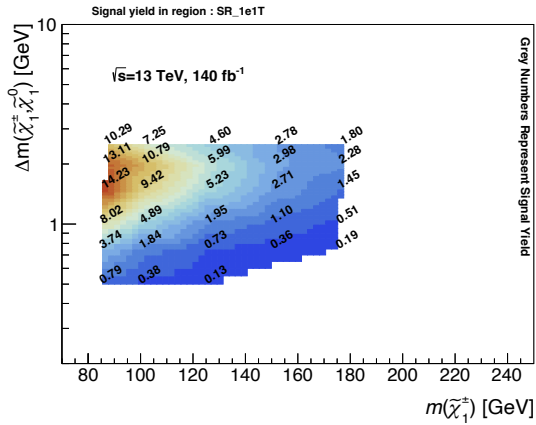
(b) $pNN-\theta = 1.5 \text{ GeV}$



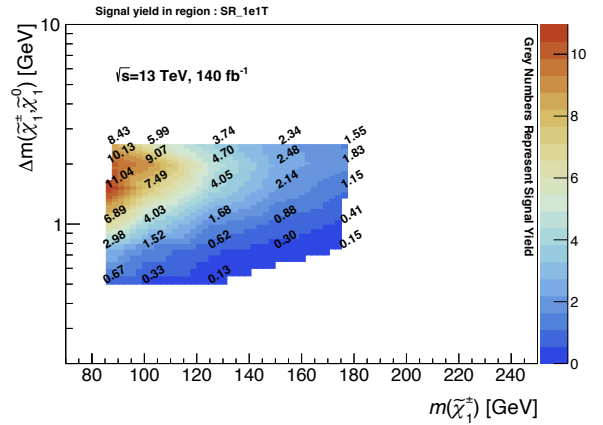
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

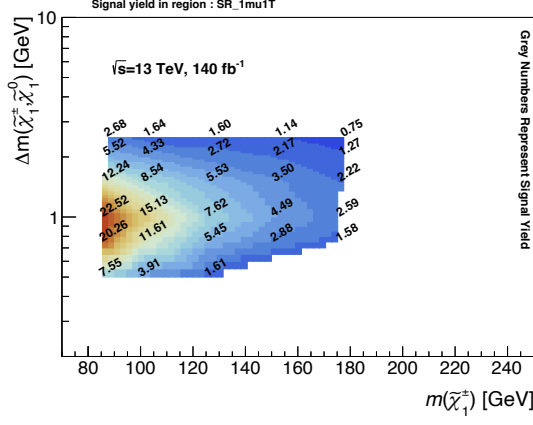


(e) $pNN-\theta = 4 \text{ GeV}$

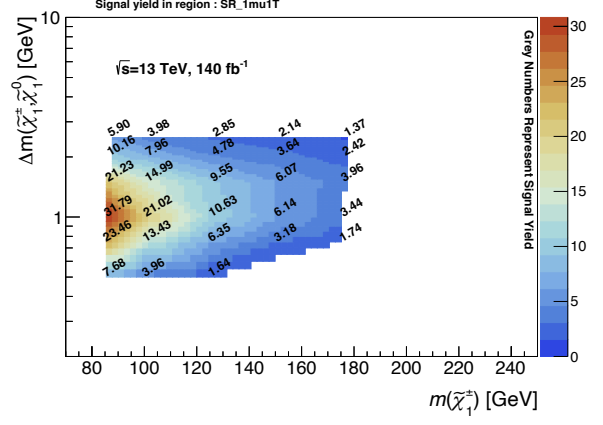


(f) $pNN-\theta = 5 \text{ GeV}$

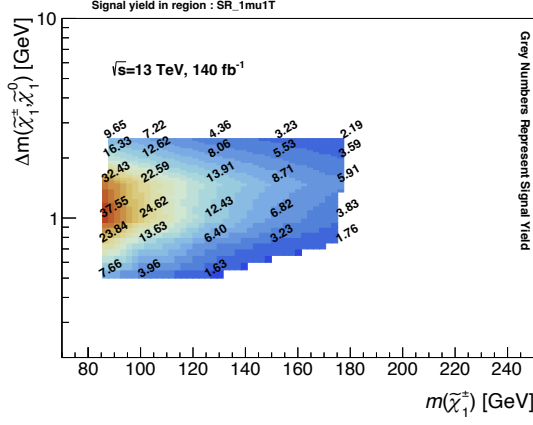
Figure C.1: Expected signal yield in SR for each mass point for the electron channel.



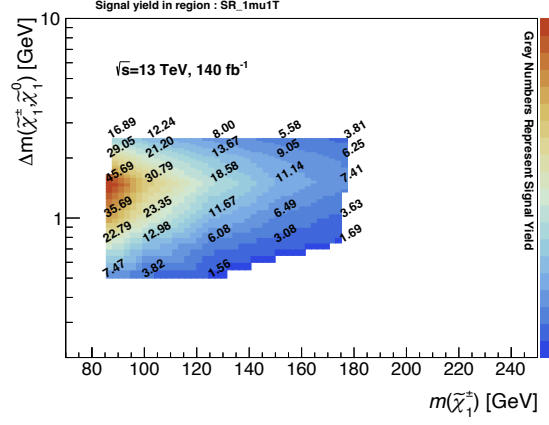
(a) $pNN-\theta = 1 \text{ GeV}$



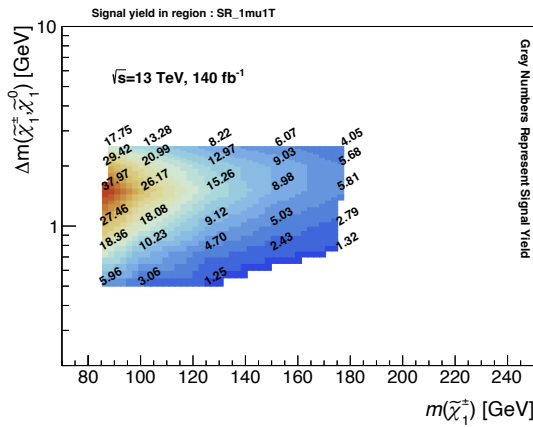
(b) $pNN-\theta = 1.5 \text{ GeV}$



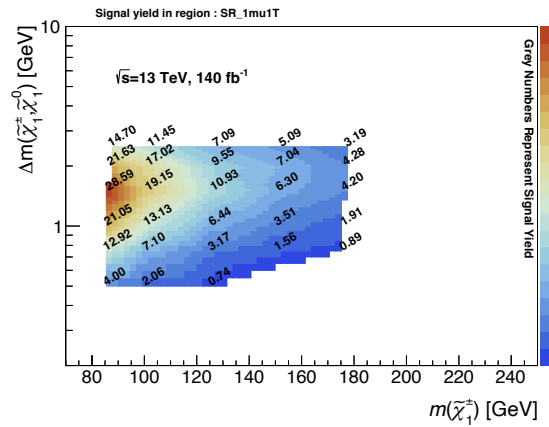
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$



(e) $pNN-\theta = 4 \text{ GeV}$



(f) $pNN-\theta = 5 \text{ GeV}$

Figure C.2: Expected signal yield in SR for each mass point for the muon channel.

D. Signal contamination

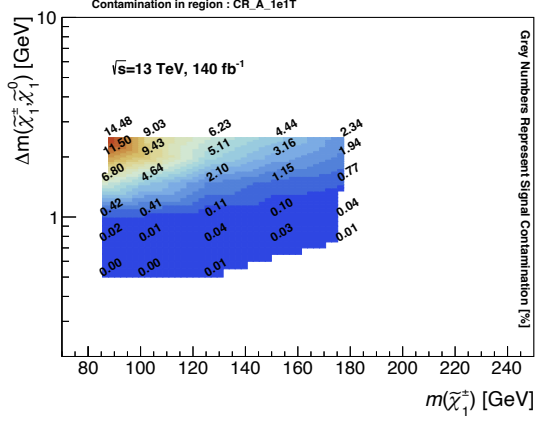
The signal contamination for each region used in the analysis has been checked to verify the validity of the background estimation method.

D.1 Control Regions

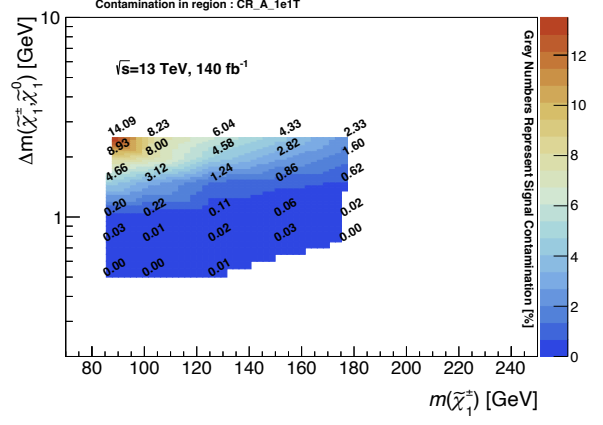
Figures [D.1-D.3](#) and [D.4-D.6](#) show the signal contamination in CR-A, CR-B, and CR-C used for estimating the background in the SRs for the electron channel and the muon channel, respectively. For both channels, contamination in CR-A is the most significant, especially for mass points with large $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ for small pNN- θ values. The contaminations are around 15% and 10% at maximum for the electron and muon channel, respectively and are sufficiently small. Moreover, the corresponding mass points with relatively large mass splittings have already been excluded by previous analyses, therefore, the effects of signal contamination for these mass points have minimal impact on the analysis.

D.2 Validation Regions

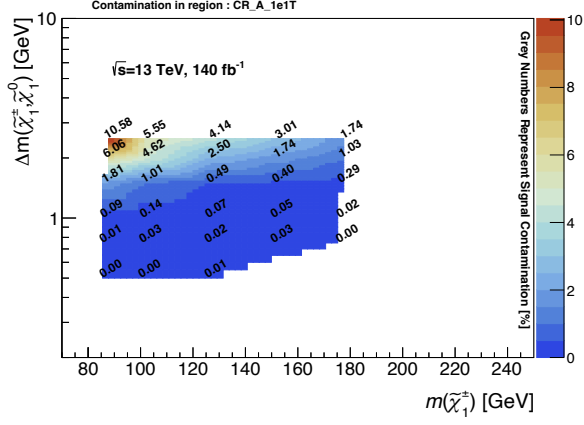
Figures [D.7-D.9](#) and [D.10-D.12](#) show the signal contamination in VRs for the electron channel and muon channel, respectively. Out of the three VRs, VR-highLarge has the most signal contamination for both channels, however, the values remain sufficiently small, typically below 10%.



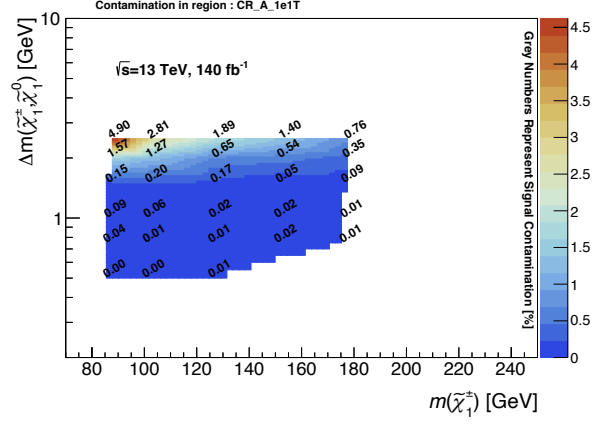
(a) $pNN-\theta = 1 \text{ GeV}$



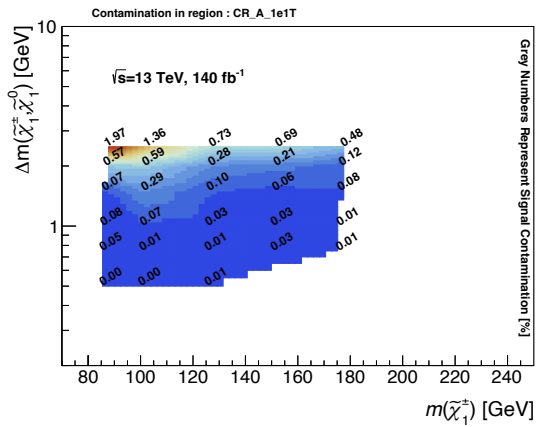
(b) $pNN-\theta = 1.5 \text{ GeV}$



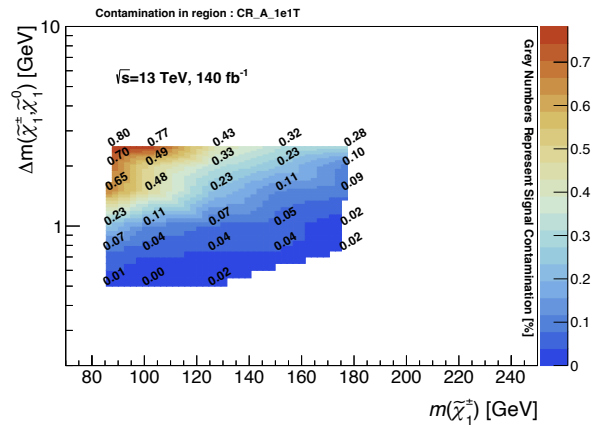
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

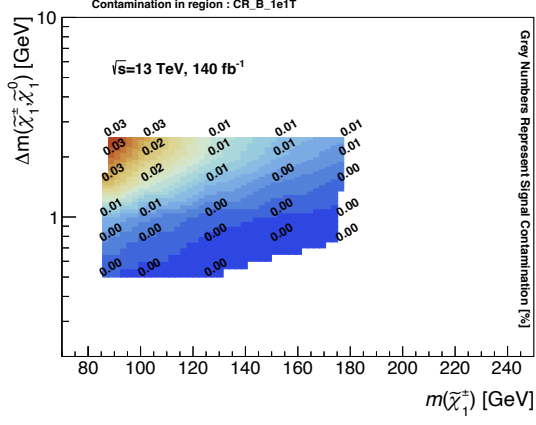


(e) $pNN-\theta = 4 \text{ GeV}$

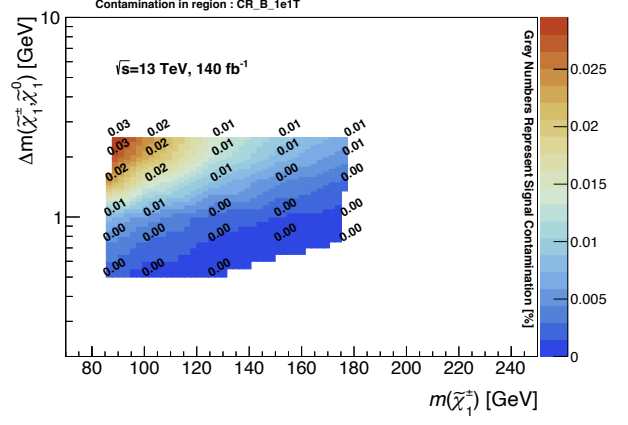


(f) $pNN-\theta = 5 \text{ GeV}$

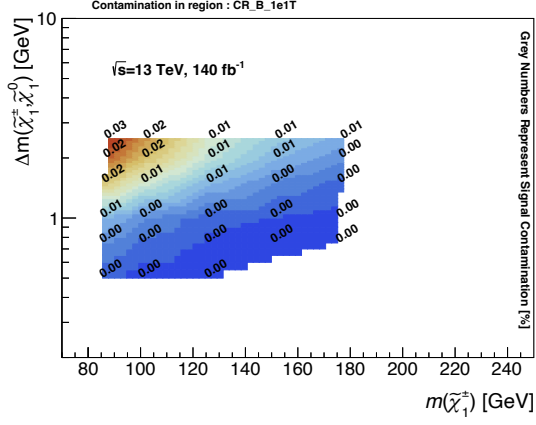
Figure D.1: Signal contamination in CR-A for each mass point for the electron channel.



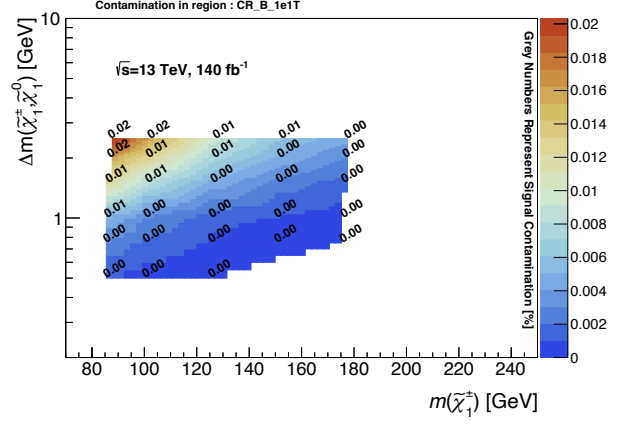
(a) pNN- θ = 1 GeV



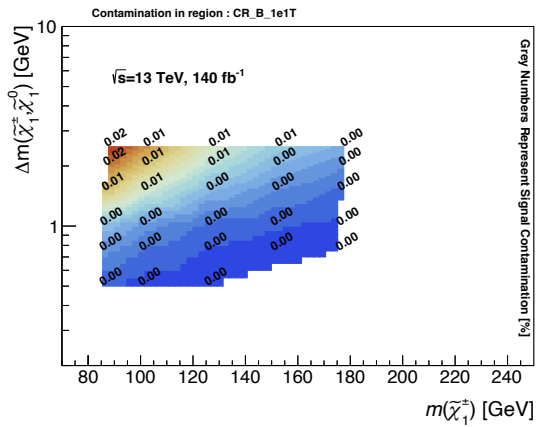
(b) pNN- θ = 1.5 GeV



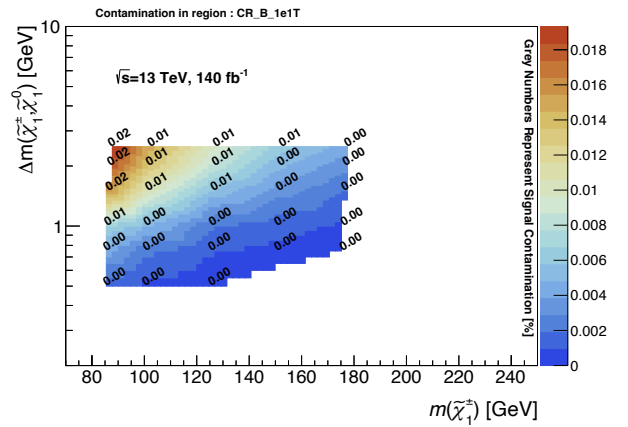
(c) pNN- θ = 2 GeV



(d) pNN- θ = 3 GeV

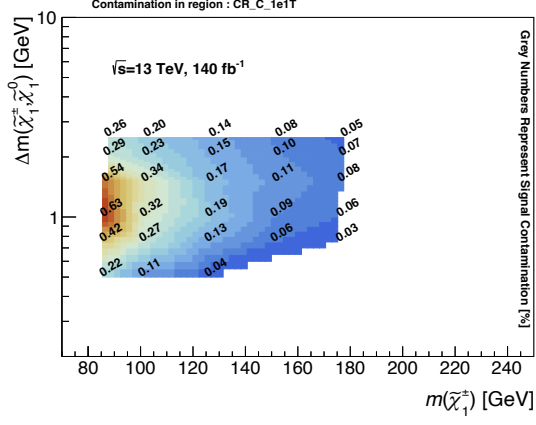


(e) pNN- θ = 4 GeV

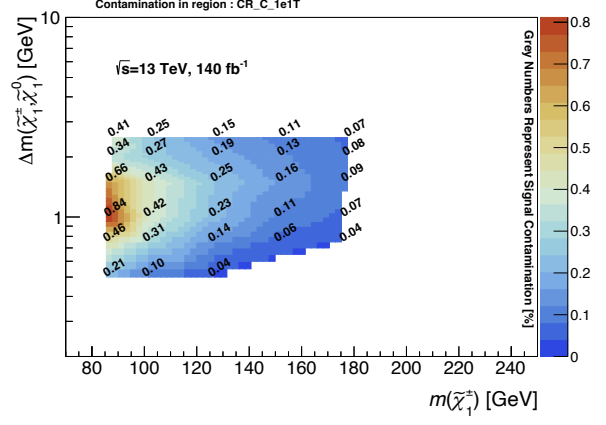


(f) pNN- θ = 5 GeV

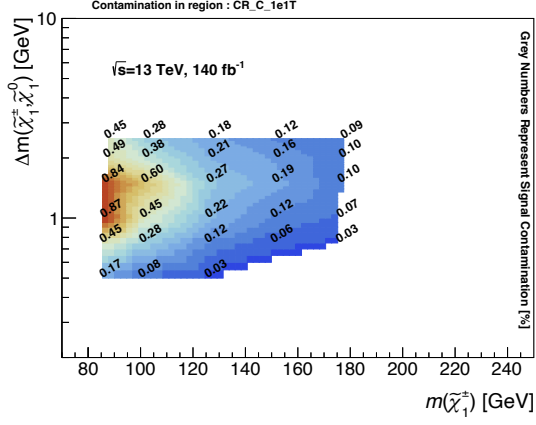
Figure D.2: Signal contamination in CR-B for each mass point for the electron channel.



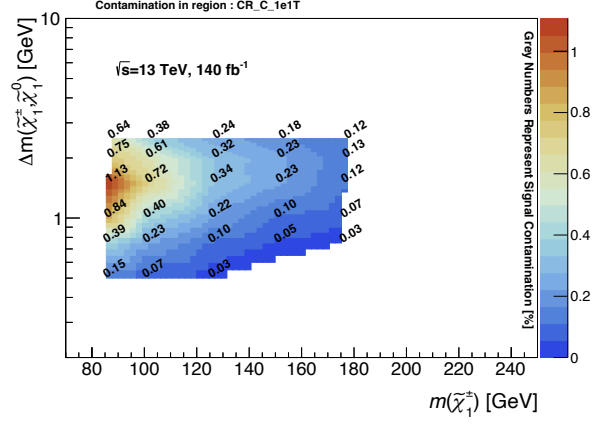
(a) $\text{pNN-}\theta = 1 \text{ GeV}$



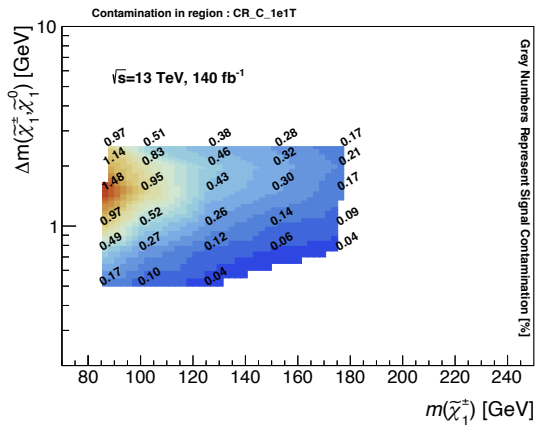
(b) $\text{pNN-}\theta = 1.5 \text{ GeV}$



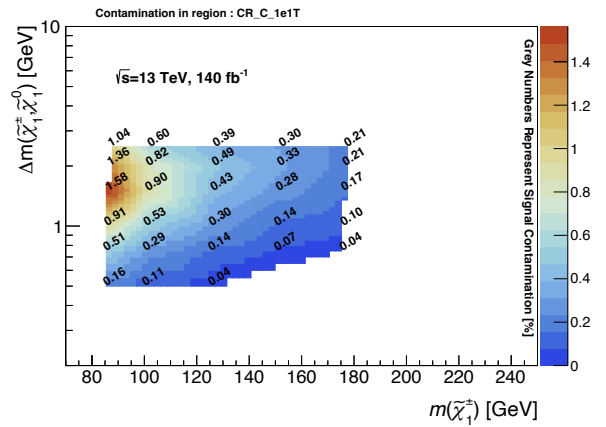
(c) $\text{pNN-}\theta = 2 \text{ GeV}$



(d) $\text{pNN-}\theta = 3 \text{ GeV}$

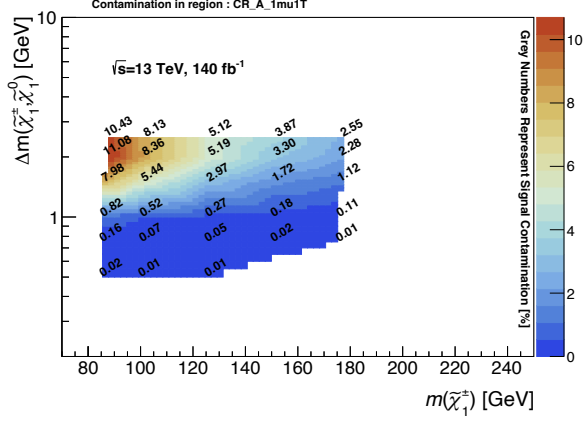


(e) $\text{pNN-}\theta = 4 \text{ GeV}$

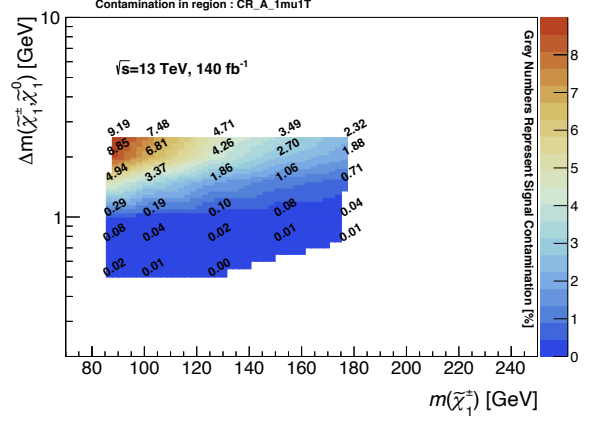


(f) $\text{pNN-}\theta = 5 \text{ GeV}$

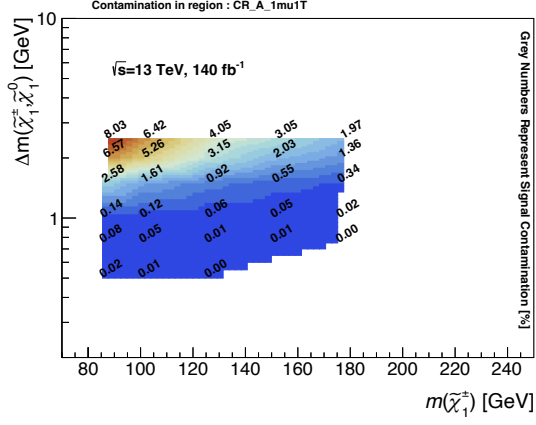
Figure D.3: Signal contamination in CR-C for each mass point for the electron channel.



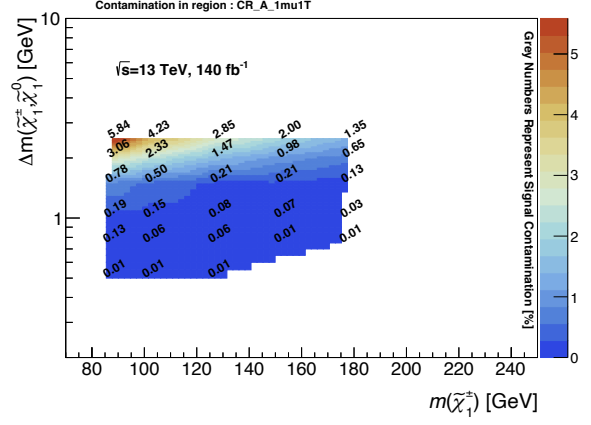
(a) pNN- θ = 1 GeV



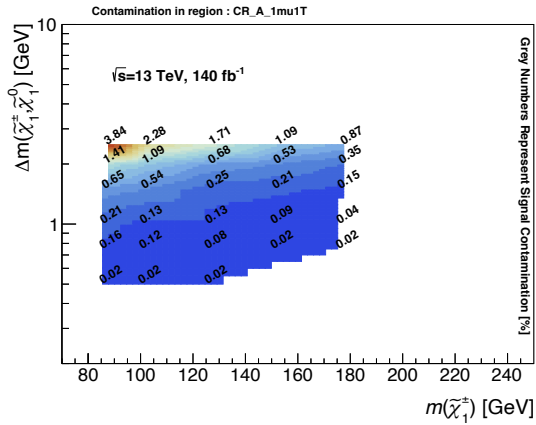
(b) pNN- θ = 1.5 GeV



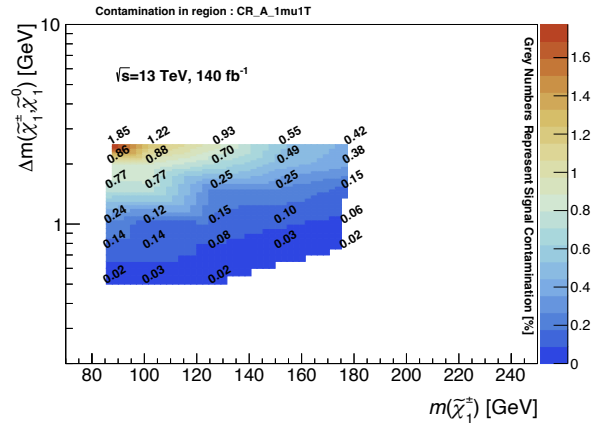
(c) pNN- θ = 2 GeV



(d) pNN- θ = 3 GeV

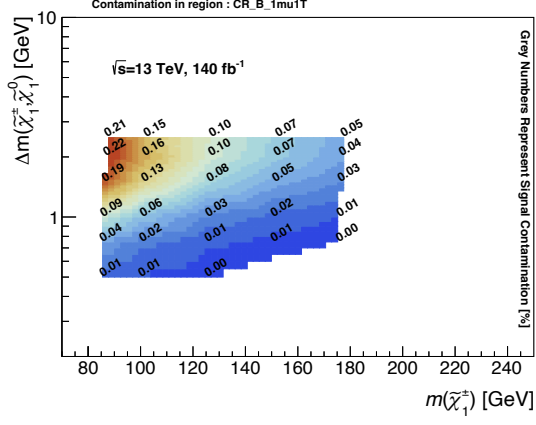


(e) pNN- θ = 4 GeV

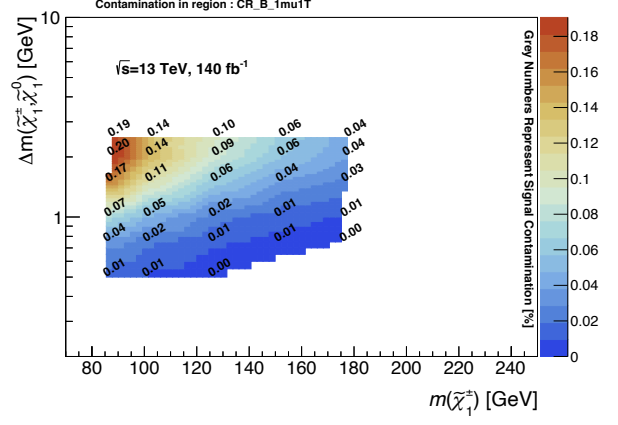


(f) pNN- θ = 5 GeV

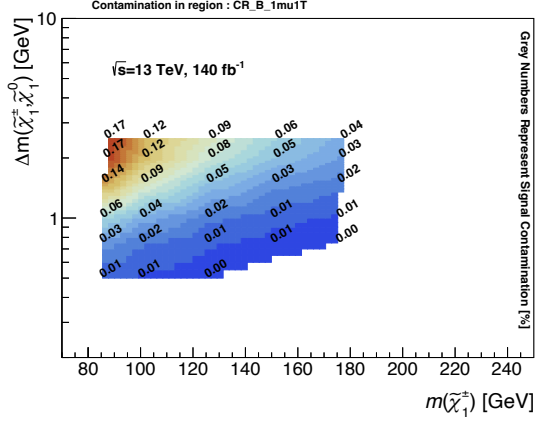
Figure D.4: Signal contamination in CR-A for each mass point for the muon channel.



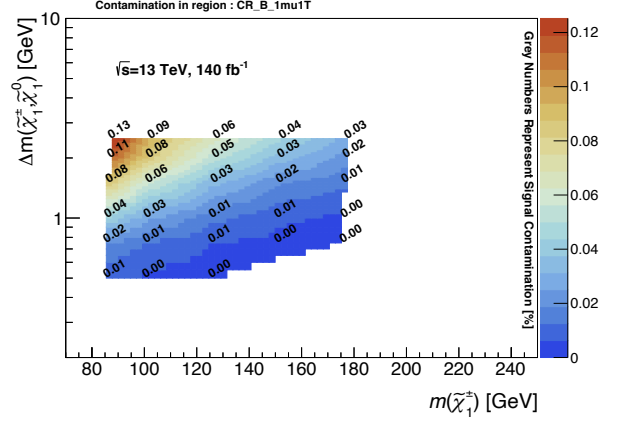
(a) $pNN-\theta = 1 \text{ GeV}$



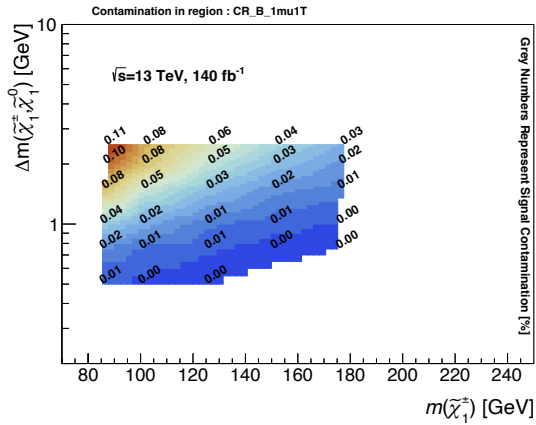
(b) $pNN-\theta = 1.5 \text{ GeV}$



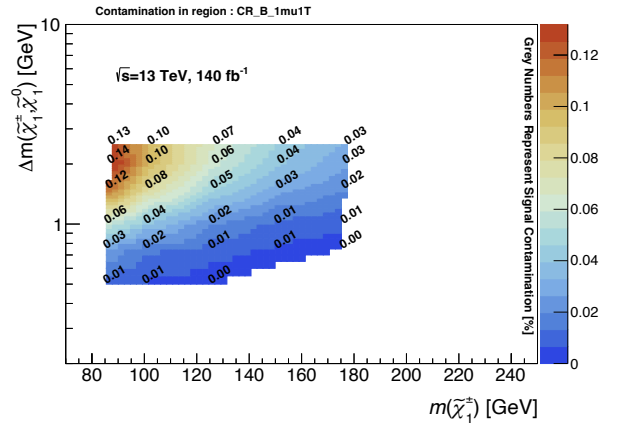
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

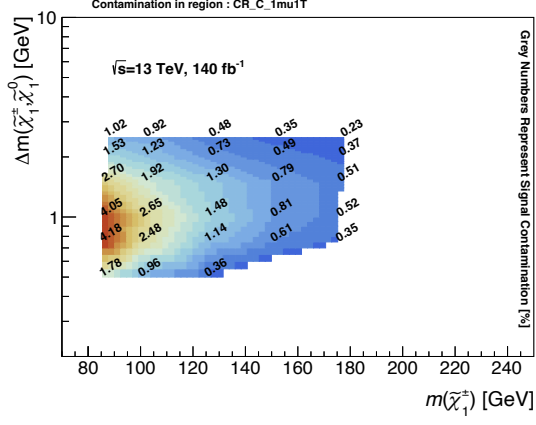


(e) $pNN-\theta = 4 \text{ GeV}$

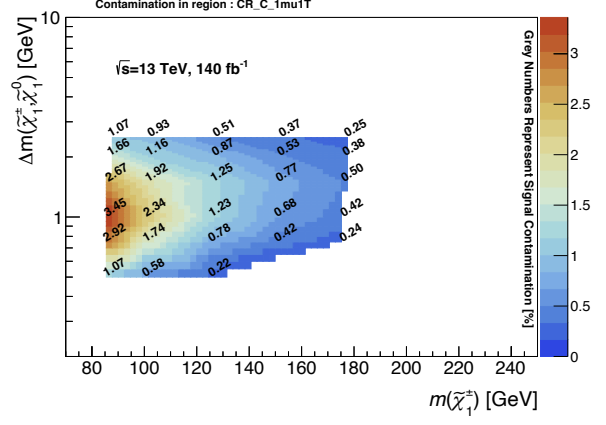


(f) $pNN-\theta = 5 \text{ GeV}$

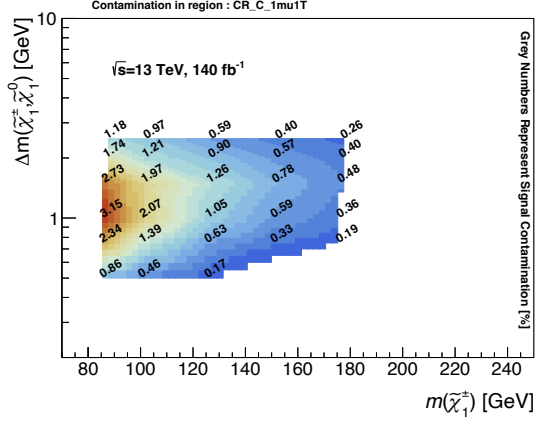
Figure D.5: Signal contamination in CR-B for each mass point for the muon channel.



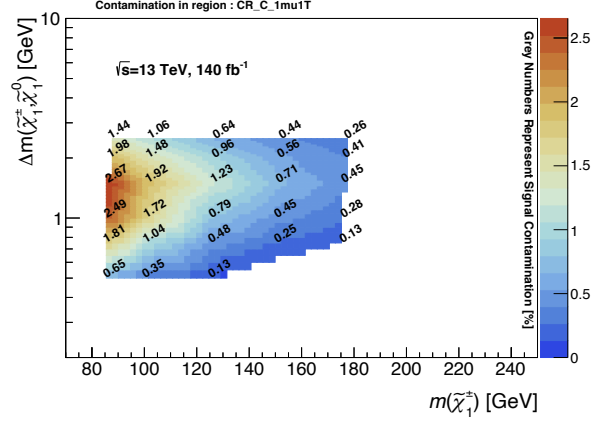
(a) $pNN-\theta = 1 \text{ GeV}$



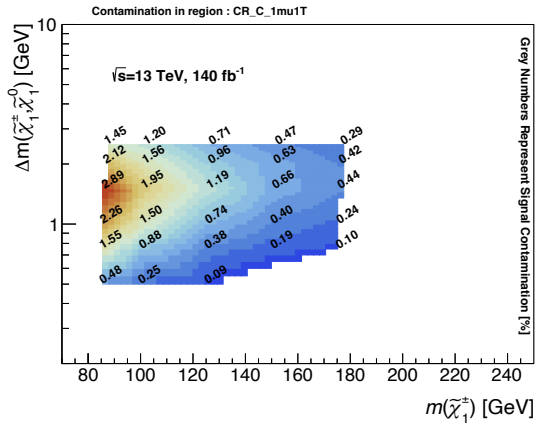
(b) $pNN-\theta = 1.5 \text{ GeV}$



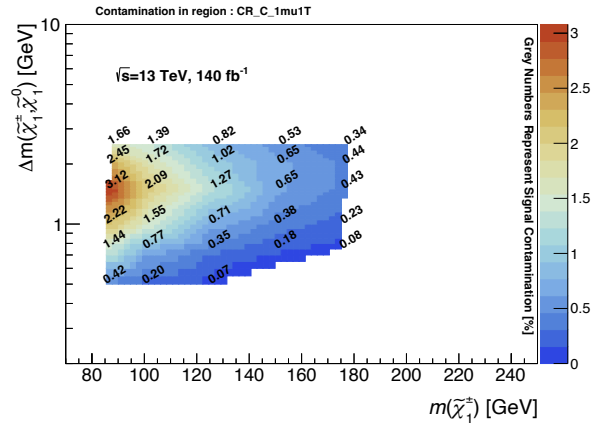
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

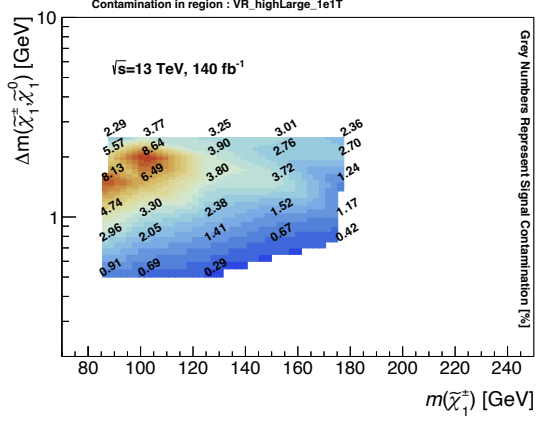


(e) $pNN-\theta = 4 \text{ GeV}$

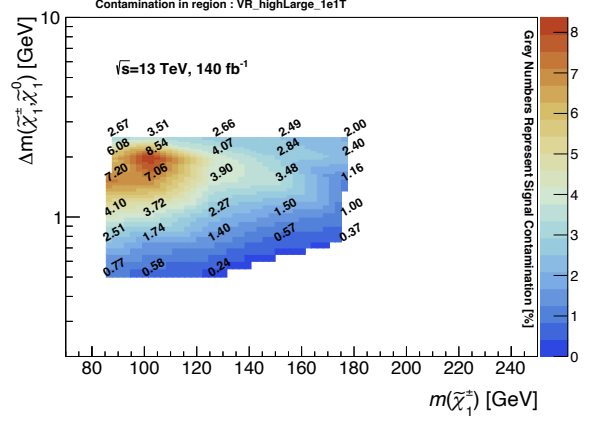


(f) $pNN-\theta = 5 \text{ GeV}$

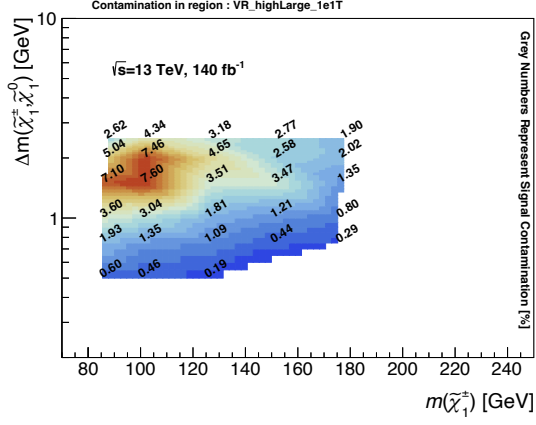
Figure D.6: Signal contamination in CR-C for each mass point for the muon channel.



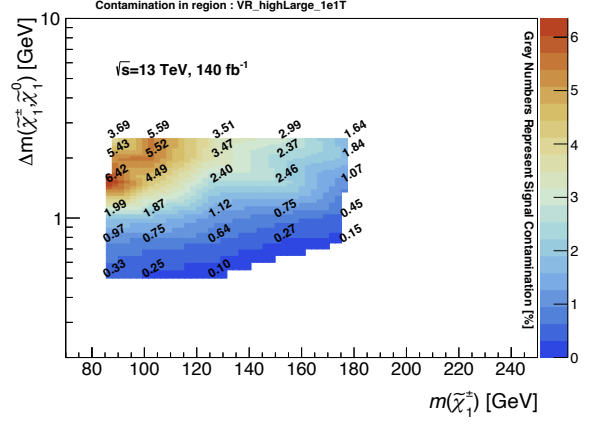
(a) $pNN-\theta = 1 \text{ GeV}$



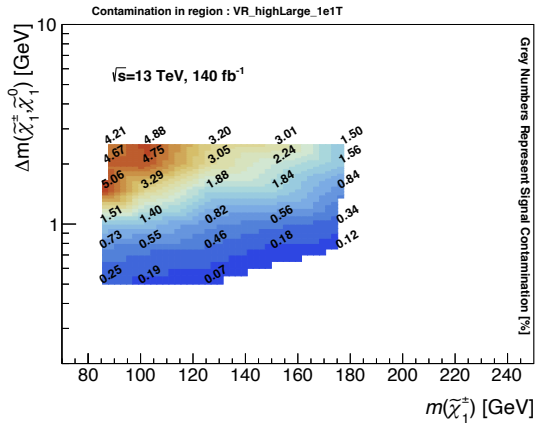
(b) $pNN-\theta = 1.5 \text{ GeV}$



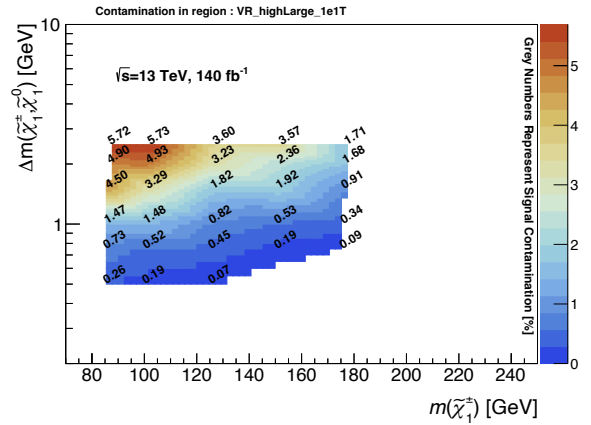
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

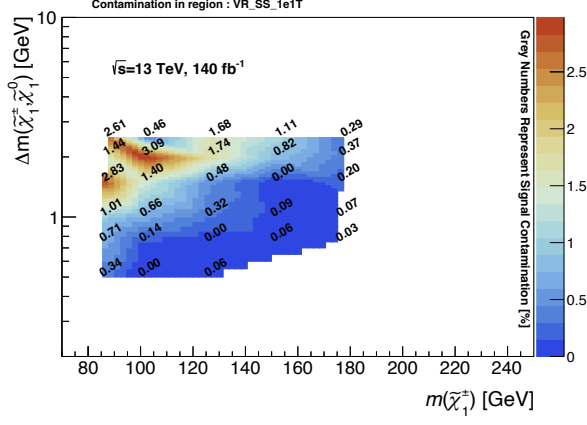


(e) $pNN-\theta = 4 \text{ GeV}$

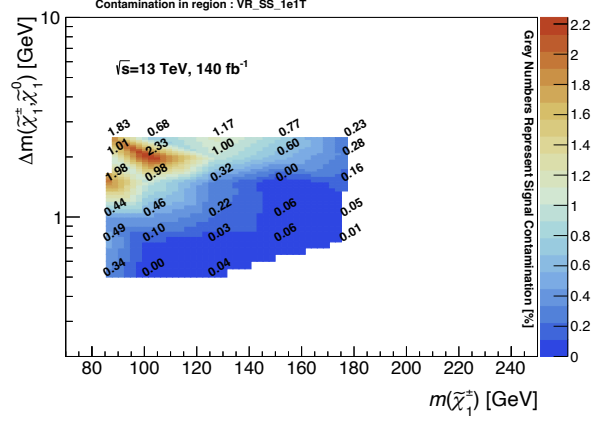


(f) $pNN-\theta = 5 \text{ GeV}$

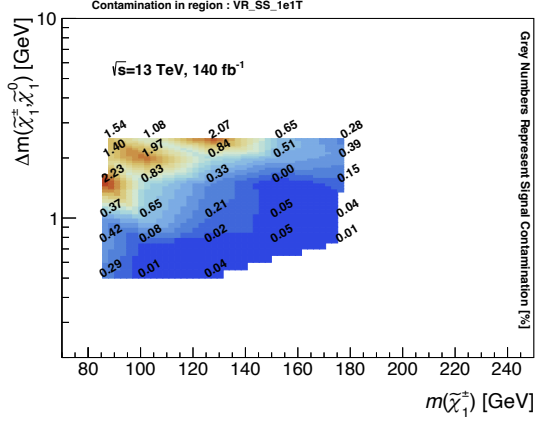
Figure D.7: Signal contamination in VR-highLarge for each mass point for the electron channel.



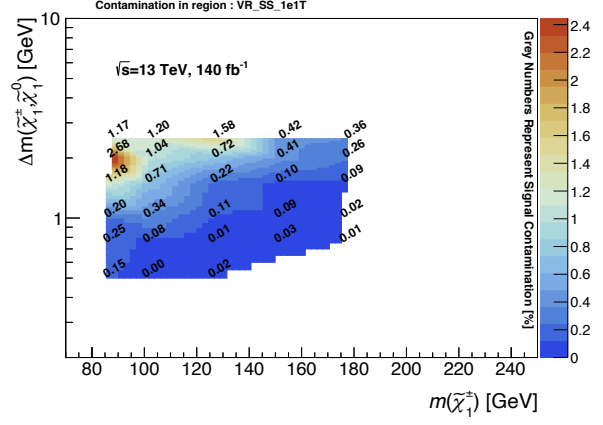
(a) pNN- $\theta = 1$ GeV



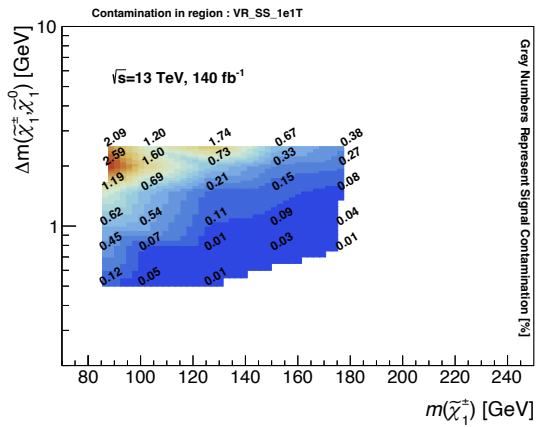
(b) pNN- $\theta = 1.5$ GeV



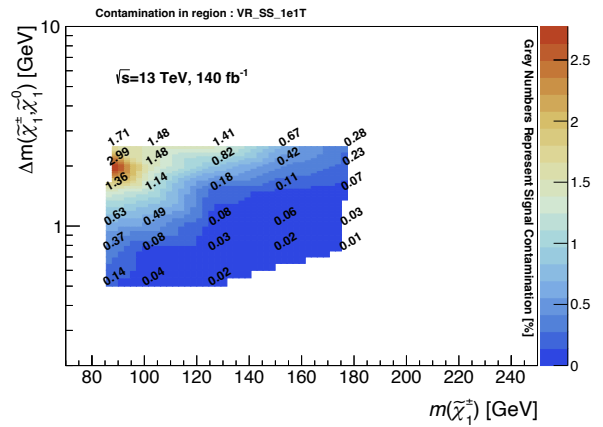
(c) pNN- $\theta = 2$ GeV



(d) pNN- $\theta = 3$ GeV

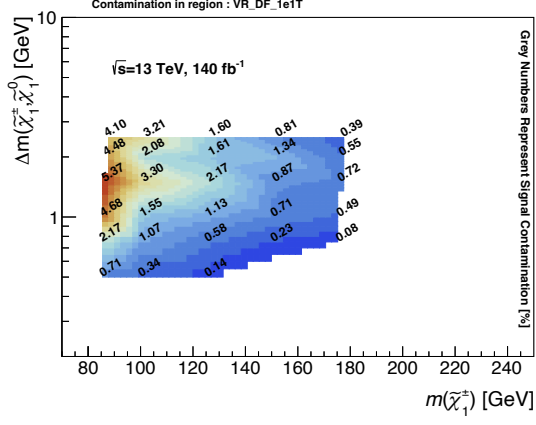


(e) pNN- $\theta = 4$ GeV

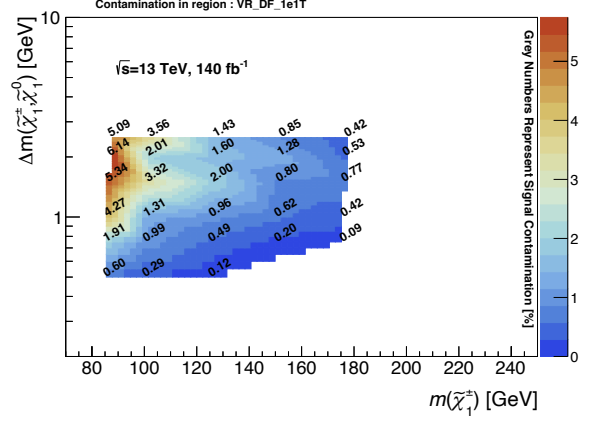


(f) pNN- $\theta = 5$ GeV

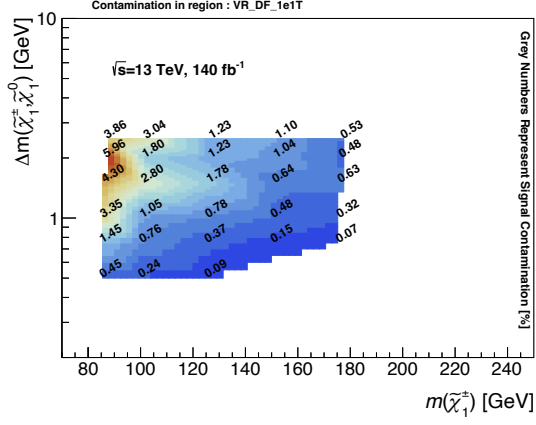
Figure D.8: Signal contamination in VR-SS for each mass point for the electron channel.



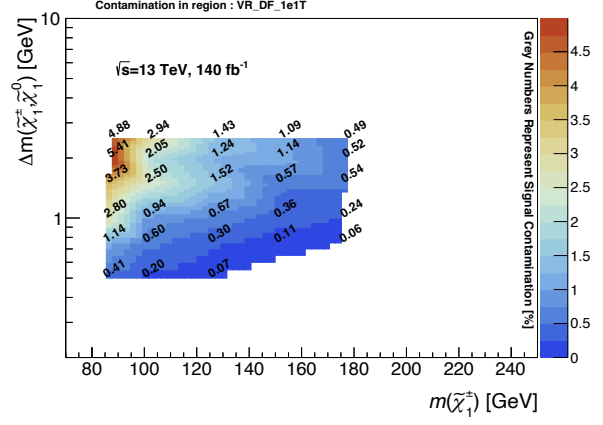
(a) pNN- θ = 1 GeV



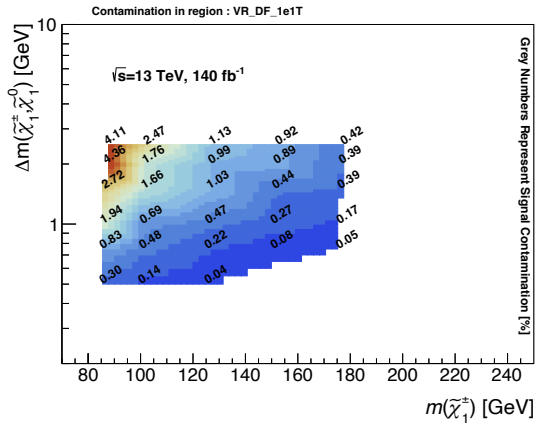
(b) pNN- θ = 1.5 GeV



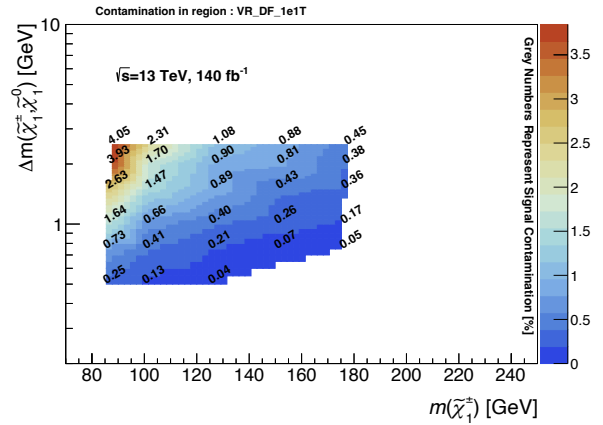
(c) pNN- θ = 2 GeV



(d) pNN- θ = 3 GeV

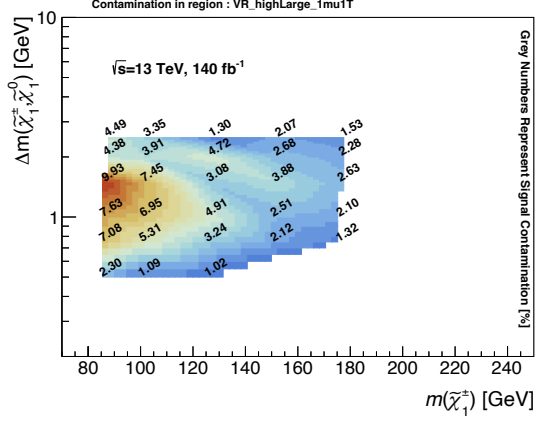


(e) pNN- θ = 4 GeV

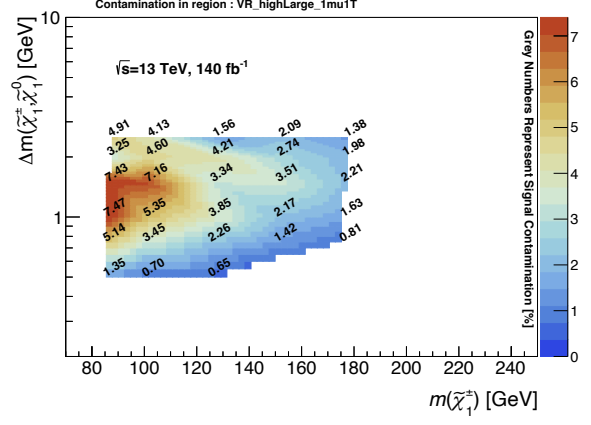


(f) pNN- θ = 5 GeV

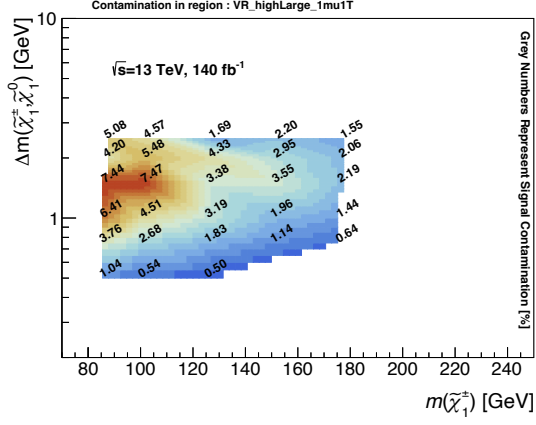
Figure D.9: Signal contamination in VR-DF for each mass point for the electron channel.



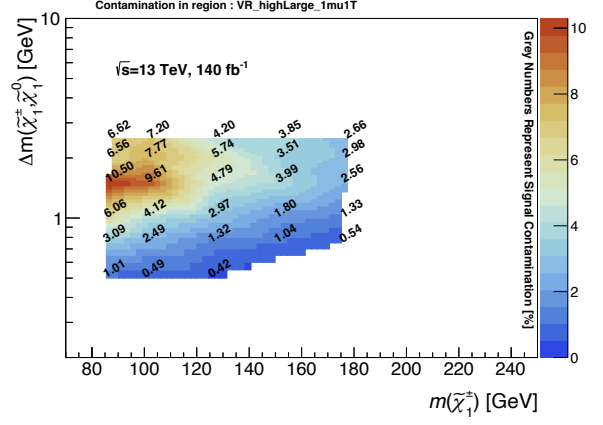
(a) $pNN-\theta = 1 \text{ GeV}$



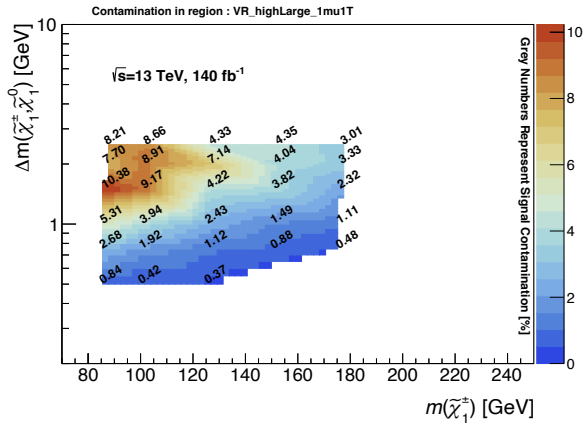
(b) $pNN-\theta = 1.5 \text{ GeV}$



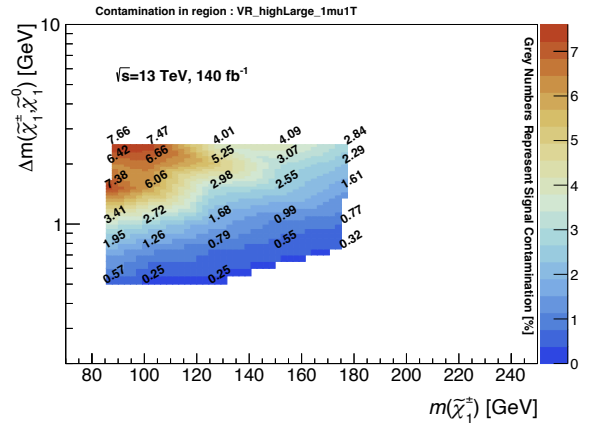
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

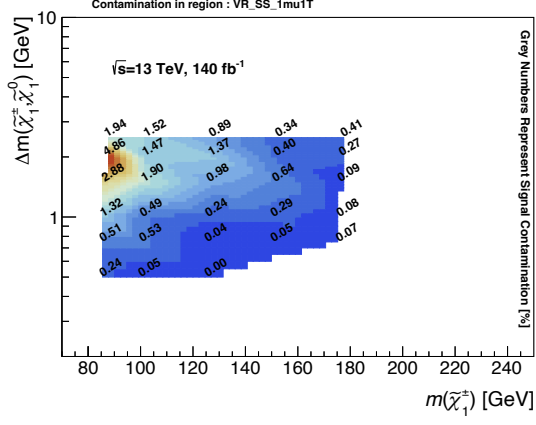


(e) $pNN-\theta = 4 \text{ GeV}$

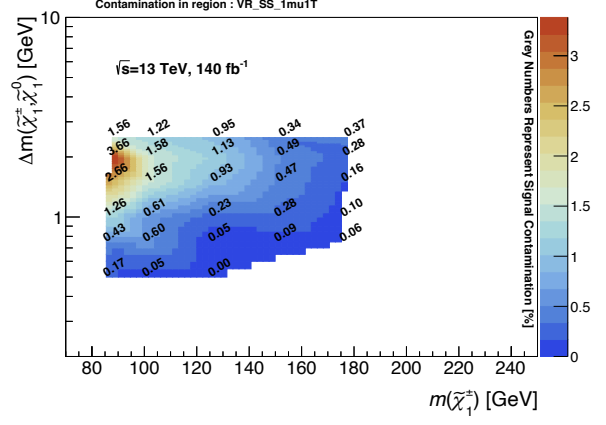


(f) $pNN-\theta = 5 \text{ GeV}$

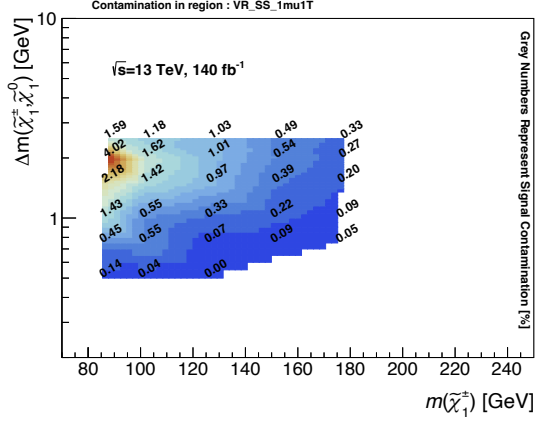
Figure D.10: Signal contamination in VR-highLarge for each mass point for the muon channel.



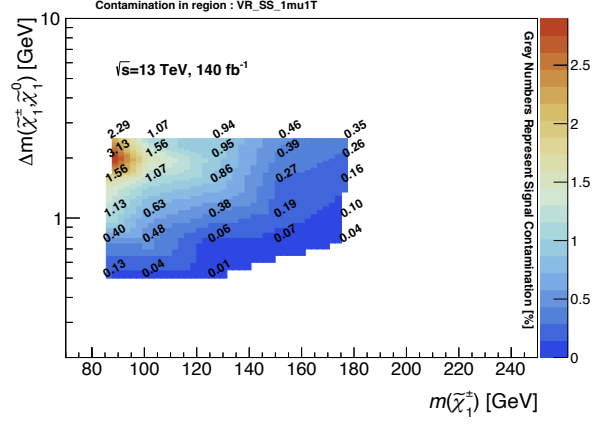
(a) $pNN-\theta = 1 \text{ GeV}$



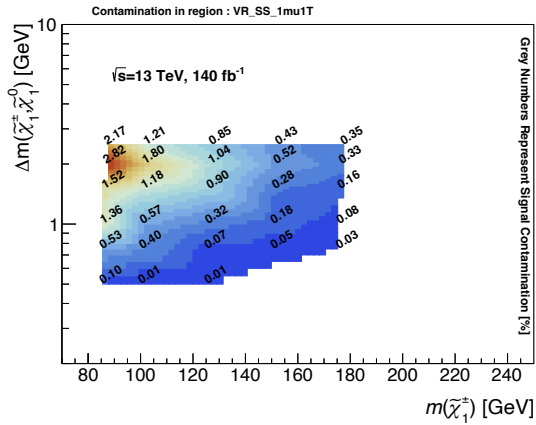
(b) $pNN-\theta = 1.5 \text{ GeV}$



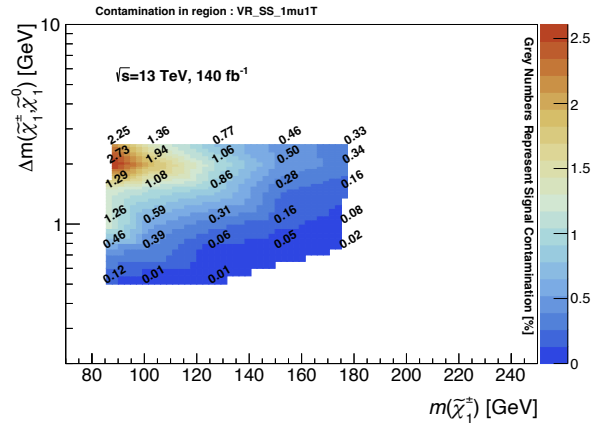
(c) $pNN-\theta = 2 \text{ GeV}$



(d) $pNN-\theta = 3 \text{ GeV}$

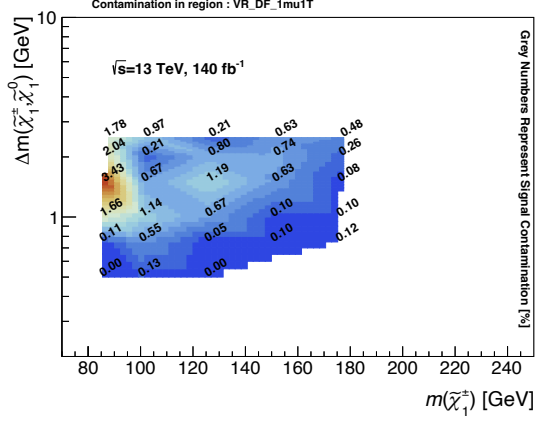


(e) $pNN-\theta = 4 \text{ GeV}$

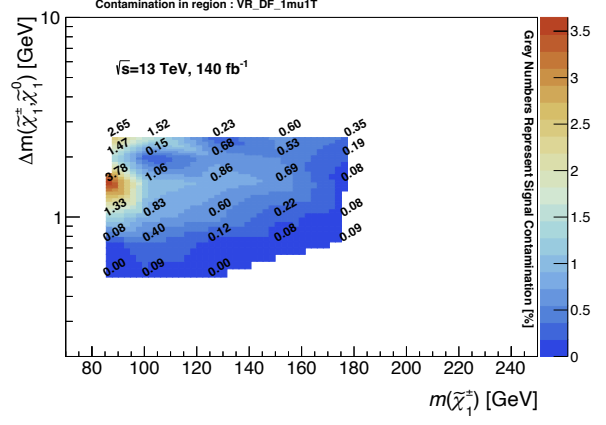


(f) $pNN-\theta = 5 \text{ GeV}$

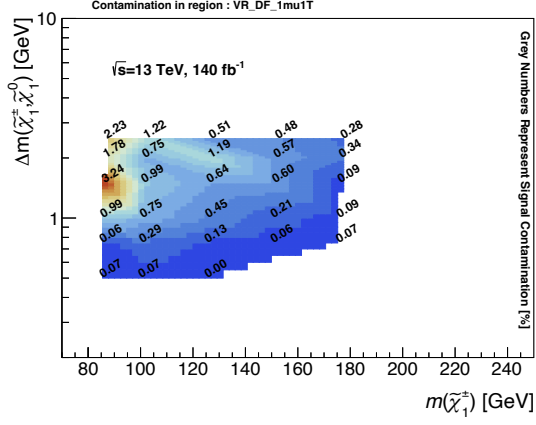
Figure D.11: Signal contamination in VR-SS for each mass point for the muon channel.



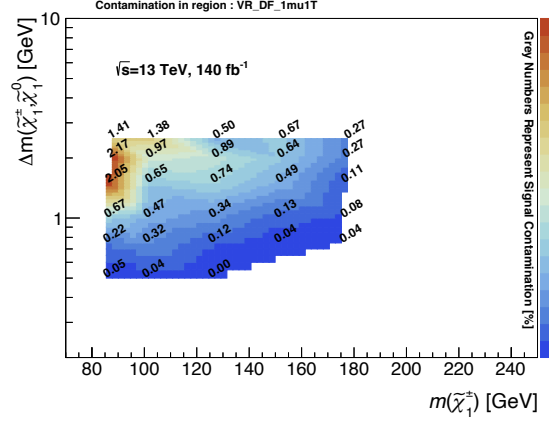
(a) pNN- θ = 1 GeV



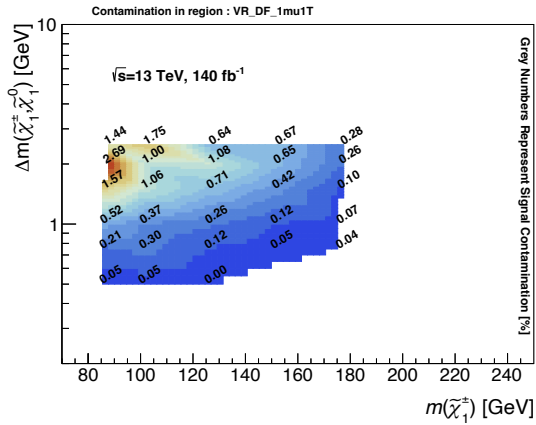
(b) pNN- θ = 1.5 GeV



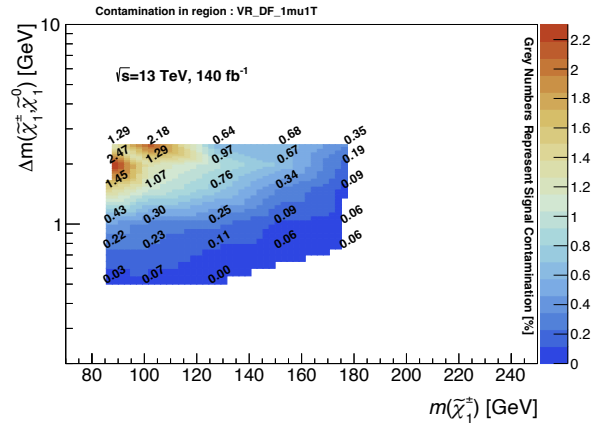
(c) pNN- θ = 2 GeV



(d) pNN- θ = 3 GeV



(e) pNN- θ = 4 GeV



(f) pNN- θ = 5 GeV

Figure D.12: Signal contamination in VR-DF for each mass point for the muon channel.

References

- [1] G. Aad et al. (ATLAS), “The ATLAS Experiment at the CERN Large Hadron Collider”, [JINST **3**, S08003 \(2008\)](#).
- [2] C. N. Yang and R. L. Mills, “Conservation of isotopic spin and isotopic gauge invariance”, [Phys. Rev. **96**, 191–195 \(1954\)](#).
- [3] S. L. Glashow, “Partial Symmetries of Weak Interactions”, [Nucl. Phys. **22**, 579–588 \(1961\)](#).
- [4] S. Weinberg, “A Model of Leptons”, [Phys. Rev. Lett. **19**, 1264–1266 \(1967\)](#).
- [5] A. Salam, “Weak and Electromagnetic Interactions”, [Conf. Proc. C **680519**, 367–377 \(1968\)](#).
- [6] G. ’t Hooft and M. J. G. Veltman, “Regularization and Renormalization of Gauge Fields”, [Nucl. Phys. B **44**, 189–213 \(1972\)](#).
- [7] D. J. Gross and F. Wilczek, “Ultraviolet Behavior of Nonabelian Gauge Theories”, [Phys. Rev. Lett. **30**, edited by J. C. Taylor, 1343–1346 \(1973\)](#).
- [8] H. D. Politzer, “Reliable Perturbative Results for Strong Interactions?”, [Phys. Rev. Lett. **30**, edited by J. C. Taylor, 1346–1349 \(1973\)](#).
- [9] F. Englert and R. Brout, “Broken Symmetry and the Mass of Gauge Vector Mesons”, [Phys. Rev. Lett. **13**, edited by J. C. Taylor, 321–323 \(1964\)](#).
- [10] P. W. Higgs, “Broken Symmetries and the Masses of Gauge Bosons”, [Phys. Rev. Lett. **13**, edited by J. C. Taylor, 508–509 \(1964\)](#).
- [11] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, “Global Conservation Laws and Massless Particles”, [Phys. Rev. Lett. **13**, edited by J. C. Taylor, 585–587 \(1964\)](#).
- [12] G. Hinshaw et al. (WMAP), “Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results”, [Astrophys. J. Suppl. **208**, 19 \(2013\)](#).
- [13] N. Aghanim et al. (Planck), “Planck 2018 results. VI. Cosmological parameters”, [Astron. Astrophys. **641**, \[Erratum: Astron.Astrophys. 652, C4 \(2021\)\], A6 \(2020\)](#).
- [14] G. Bertone, D. Hooper, and J. Silk, “Particle dark matter: Evidence, candidates and constraints”, [Phys. Rept. **405**, 279–390 \(2005\)](#).
- [15] J. L. Feng, “Dark Matter Candidates from Particle Physics and Methods of Detection”, [Ann. Rev. Astron. Astrophys. **48**, 495–545 \(2010\)](#).
- [16] Y. Fukuda et al. (Super-Kamiokande), “Evidence for oscillation of atmospheric neutrinos”, [Phys. Rev. Lett. **81**, 1562–1567 \(1998\)](#).

- [17] Q. R. Ahmad et al. (SNO), “Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory”, [Phys. Rev. Lett. **89**, 011301 \(2002\)](#).
- [18] H. Georgi and S. L. Glashow, “Unity of All Elementary Particle Forces”, [Phys. Rev. Lett. **32**, 438–441 \(1974\)](#).
- [19] H. Fritzsch and P. Minkowski, “Unified Interactions of Leptons and Hadrons”, [Annals Phys. **93**, 193–266 \(1975\)](#).
- [20] A. J. Buras, J. R. Ellis, M. K. Gaillard, and D. V. Nanopoulos, “Aspects of the Grand Unification of Strong, Weak and Electromagnetic Interactions”, [Nucl. Phys. B **135**, 66–92 \(1978\)](#).
- [21] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, “The Hierarchy problem and new dimensions at a millimeter”, [Phys. Lett. B **429**, 263–272 \(1998\)](#).
- [22] Y. A. Golfand and E. P. Likhtman, “Extension of the Algebra of Poincare Group Generators and Violation of p Invariance”, [JETP Lett. **13**, 323–326 \(1971\)](#).
- [23] D. V. Volkov and V. P. Akulov, “Is the Neutrino a Goldstone Particle?”, [Phys. Lett. B **46**, 109–110 \(1973\)](#).
- [24] J. Wess and B. Zumino, “Supergauge Transformations in Four-Dimensions”, [Nucl. Phys. B **70**, edited by A. Salam and E. Sezgin, 39–50 \(1974\)](#).
- [25] J. Wess and B. Zumino, “Supergauge Invariant Extension of Quantum Electrodynamics”, [Nucl. Phys. B **78**, 1 \(1974\)](#).
- [26] S. Ferrara and B. Zumino, “Supergauge Invariant Yang-Mills Theories”, [Nucl. Phys. B **79**, 413 \(1974\)](#).
- [27] A. Salam and J. A. Strathdee, “Super-symmetry and non-Abelian gauges”, [Phys. Lett. B **51**, 353–355 \(1974\)](#).
- [28] S. P. Martin, “A Supersymmetry Primer”, [Adv. Ser. Direct. High Energy Phys. **18**, edited by G. L. Kane, 1–98 \(1998\)](#).
- [29] P. Ramond, “Dual Theory for Free Fermions”, [Phys. Rev. D **3**, 2415–2418 \(1971\)](#).
- [30] A. Neveu and J. H. Schwarz, “Factorizable dual model of pions”, [Nucl. Phys. B **31**, 86–112 \(1971\)](#).
- [31] R. Haag, J. T. Lopuszanski, and M. Sohnius, “All Possible Generators of Supersymmetries of the s Matrix”, [Nucl. Phys. B **88**, 257 \(1975\)](#).
- [32] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, “Supersymmetric Relics from the Big Bang”, [Nucl. Phys. B **238**, edited by M. A. Srednicki, 453–476 \(1984\)](#).
- [33] G. Jungman, M. Kamionkowski, and K. Griest, “Supersymmetric dark matter”, [Phys. Rept. **267**, 195–373 \(1996\)](#).
- [34] N. Sakai, “Naturalness in Supersymmetric Guts”, [Z. Phys. C **11**, 153 \(1981\)](#).
- [35] S. Dimopoulos, S. Raby, and F. Wilczek, “Supersymmetry and the Scale of Unification”, [Phys. Rev. D **24**, 1681–1683 \(1981\)](#).

- [36] L. E. Ibanez and G. G. Ross, “Low-Energy Predictions in Supersymmetric Grand Unified Theories”, [Phys. Lett. B **105**, 439–442 \(1981\)](#).
- [37] S. Dimopoulos and H. Georgi, “Softly Broken Supersymmetry and SU(5)”, [Nucl. Phys. B **193**, 150–162 \(1981\)](#).
- [38] R. Barbieri and G. F. Giudice, “Upper Bounds on Supersymmetric Particle Masses”, [Nucl. Phys. B **306**, 63–76 \(1988\)](#).
- [39] G. F. Giudice and A. Masiero, “A Natural Solution to the mu Problem in Supergravity Theories”, [Phys. Lett. B **206**, 480–484 \(1988\)](#).
- [40] B. de Carlos and J. A. Casas, “One loop analysis of the electroweak breaking in supersymmetric models and the fine tuning problem”, [Phys. Lett. B **309**, 320–328 \(1993\)](#).
- [41] R. Barbieri and D. Pappadopulo, “S-particles at their naturalness limits”, [JHEP **10**, 061 \(2009\)](#).
- [42] H. Baer, V. Barger, and P. Huang, “Hidden susy at the lhc: the light higgsino-world scenario and the role of a lepton collider”, [Journal of High Energy Physics **2011**, 10.1007/jhep11\(2011\)031 \(2011\)](#).
- [43] M. Papucci, J. T. Ruderman, and A. Weiler, “Natural SUSY Endures”, [JHEP **09**, 035 \(2012\)](#).
- [44] H. Baer, V. Barger, P. Huang, A. Mustafayev, and X. Tata, “Radiative natural SUSY with a 125 GeV Higgs boson”, [Phys. Rev. Lett. **109**, 161802 \(2012\)](#).
- [45] P. Fayet, “Supersymmetry and Weak, Electromagnetic and Strong Interactions”, [Phys. Lett. B **64**, 159 \(1976\)](#).
- [46] P. Fayet, “Spontaneously Broken Supersymmetric Theories of Weak, Electromagnetic and Strong Interactions”, [Phys. Lett. B **69**, 489 \(1977\)](#).
- [47] R. L. Workman et al. (Particle Data Group), “Review of Particle Physics”, [PTEP **2022**, 083C01 \(2022\)](#).
- [48] V. C. Rubin and W. K. Ford Jr., “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions”, [Astrophys. J. **159**, 379–403 \(1970\)](#).
- [49] M. Roberts and R. Whitehurst, “The rotation curve and geometry of M31 at large galactocentric distances”, [Astrophys. J. **201**, 327–346 \(1975\)](#).
- [50] D. Walsh, R. F. Carswell, and R. J. Weymann, “0957 + 561 A, B - Twin quasistellar objects or gravitational lens”, [Nature **279**, 381–384 \(1979\)](#).
- [51] K. G. Begeman, A. H. Broeils, and R. H. Sanders, “Extended rotation curves of spiral galaxies: Dark haloes and modified dynamics”, [Mon. Not. Roy. Astron. Soc. **249**, 523 \(1991\)](#).
- [52] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, “A Theory of Dark Matter”, [Phys. Rev. D **79**, 015014 \(2009\)](#).
- [53] R. D. Peccei and H. R. Quinn, “CP Conservation in the Presence of Pseudoparticles”, [Phys. Rev. Lett. **38**, 1440–1443 \(1977\)](#).
- [54] R. D. Peccei and H. R. Quinn, “Constraints Imposed by CP Conservation in the Presence of Pseudoparticles”, [Phys. Rev. D **16**, 1791–1797 \(1977\)](#).

- [55] F. Wilczek, “Problem of Strong P and T Invariance in the Presence of Instantons”, [Phys. Rev. Lett. **40**, 279–282 \(1978\)](#).
- [56] S. Weinberg, “A New Light Boson?”, [Phys. Rev. Lett. **40**, 223–226 \(1978\)](#).
- [57] P. H. Frampton, M. Kawasaki, F. Takahashi, and T. T. Yanagida, “Primordial Black Holes as All Dark Matter”, [JCAP **04**, 023 \(2010\)](#).
- [58] B. Carr, F. Kuhnel, and M. Sandstad, “Primordial Black Holes as Dark Matter”, [Phys. Rev. D **94**, 083504 \(2016\)](#).
- [59] A. M. Green and B. J. Kavanagh, “Primordial Black Holes as a dark matter candidate”, [J. Phys. G **48**, 043001 \(2021\)](#).
- [60] A. Ashtekar, “New Variables for Classical and Quantum Gravity”, [Phys. Rev. Lett. **57**, 2244–2247 \(1986\)](#).
- [61] A. Ashtekar, “New Hamiltonian Formulation of General Relativity”, [Phys. Rev. D **36**, 1587–1602 \(1987\)](#).
- [62] C. Rovelli and L. Smolin, “Knot Theory and Quantum Gravity”, [Phys. Rev. Lett. **61**, 1155 \(1988\)](#).
- [63] C. Rovelli and L. Smolin, “Loop Space Representation of Quantum General Relativity”, [Nucl. Phys. B **331**, 80–152 \(1990\)](#).
- [64] C. Rovelli and L. Smolin, “Discreteness of area and volume in quantum gravity”, [Nucl. Phys. B **442**, \[Erratum: Nucl.Phys.B 456, 753–754 \(1995\)\], 593–622 \(1995\)](#).
- [65] P. Nath and R. L. Arnowitt, “Generalized Supergauge Symmetry as a New Framework for Unified Gauge Theories”, [Phys. Lett. B **56**, 177–180 \(1975\)](#).
- [66] R. L. Arnowitt, P. Nath, and B. Zumino, “Superfield Densities and Action Principle in Curved Superspace”, [Phys. Lett. B **56**, 81–84 \(1975\)](#).
- [67] D. Z. Freedman, P. van Nieuwenhuizen, and S. Ferrara, “Progress Toward a Theory of Supergravity”, [Phys. Rev. D **13**, 3214–3218 \(1976\)](#).
- [68] S. Deser and B. Zumino, “Consistent Supergravity”, [Phys. Lett. B **62**, edited by A. Salam and E. Sezgin, 335 \(1976\)](#).
- [69] D. Z. Freedman and P. van Nieuwenhuizen, “Properties of Supergravity Theory”, [Phys. Rev. D **14**, 912 \(1976\)](#).
- [70] E. Cremmer, B. Julia, J. Scherk, S. Ferrara, L. Girardello, and P. van Nieuwenhuizen, “Spontaneous symmetry breaking and higgs effect in supergravity without cosmological constant”, [Nuclear Physics B **147**, 105–131 \(1979\)](#).
- [71] J. A. Bagger, “Coupling the Gauge Invariant Supersymmetric Nonlinear Sigma Model to Supergravity”, [Nucl. Phys. B **211**, 302 \(1983\)](#).
- [72] E. Cremmer, S. Ferrara, L. Girardello, and A. Van Proeyen, “Yang-Mills Theories with Local Supersymmetry: Lagrangian, Transformation Laws and SuperHiggs Effect”, [Nucl. Phys. B **212**, edited by A. Salam and E. Sezgin, 413 \(1983\)](#).
- [73] M. Dine and W. Fischler, “A Phenomenological Model of Particle Physics Based on Supersymmetry”, [Phys. Lett. B **110**, 227–231 \(1982\)](#).

- [74] C. R. Nappi and B. A. Ovrut, “Supersymmetric extension of the $su(3) \times su(2) \times u(1)$ model”, [Physics Letters B **113**, 175–179 \(1982\)](#).
- [75] L. Alvarez-Gaume, M. Claudson, and M. B. Wise, “Low-Energy Supersymmetry”, [Nucl. Phys. B **207**, 96 \(1982\)](#).
- [76] M. Dine and A. E. Nelson, “Dynamical supersymmetry breaking at low-energies”, [Phys. Rev. D **48**, 1277–1287 \(1993\)](#).
- [77] M. Dine, A. E. Nelson, and Y. Shirman, “Low-energy dynamical supersymmetry breaking simplified”, [Phys. Rev. D **51**, 1362–1370 \(1995\)](#).
- [78] M. Dine, A. E. Nelson, Y. Nir, and Y. Shirman, “New tools for low-energy dynamical supersymmetry breaking”, [Phys. Rev. D **53**, 2658–2669 \(1996\)](#).
- [79] L. Randall and R. Sundrum, “Out of this world supersymmetry breaking”, [Nucl. Phys. B **557**, 79–118 \(1999\)](#).
- [80] G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi, “Gaugino mass without singlets”, [JHEP **12**, 027 \(1998\)](#).
- [81] T. Falk, K. A. Olive, and M. Srednicki, “Heavy sneutrinos as dark matter”, [Phys. Lett. B **339**, 248–251 \(1994\)](#).
- [82] K. Griest and D. Seckel, “Three exceptions in the calculation of relic abundances”, [Phys. Rev. D **43**, 3191–3203 \(1991\)](#).
- [83] J. R. Ellis, T. Falk, and K. A. Olive, “Neutralino - Stau coannihilation and the cosmological upper limit on the mass of the lightest supersymmetric particle”, [Phys. Lett. B **444**, 367–372 \(1998\)](#).
- [84] J. R. Ellis, T. Falk, K. A. Olive, and M. Srednicki, “Calculations of neutralino-stau coannihilation channels and the cosmologically relevant region of MSSM parameter space”, [Astropart. Phys. **13**, \[Erratum: Astropart.Phys. 15, 413–414 \(2001\)\], 181–213 \(2000\)](#).
- [85] T. Gherghetta, G. F. Giudice, and J. D. Wells, “Phenomenological consequences of supersymmetry with anomaly induced masses”, [Nucl. Phys. B **559**, 27–47 \(1999\)](#).
- [86] T. Moroi and L. Randall, “Wino cold dark matter from anomaly mediated SUSY breaking”, [Nucl. Phys. B **570**, 455–472 \(2000\)](#).
- [87] B. Murakami and J. D. Wells, “Nucleon scattering with higgsino and wino cold dark matter”, [Phys. Rev. D **64**, 015001 \(2001\)](#).
- [88] T. Moroi, H. Murayama, and M. Yamaguchi, “Cosmological constraints on the light stable gravitino”, [Phys. Lett. B **303**, 289–294 \(1993\)](#).
- [89] M. Bolz, A. Brandenburg, and W. Buchmuller, “Thermal production of gravitinos”, [Nucl. Phys. B **606**, \[Erratum: Nucl.Phys.B 790, 336–337 \(2008\)\], 518–544 \(2001\)](#).
- [90] V. S. Rychkov and A. Strumia, “Thermal production of gravitinos”, [Phys. Rev. D **75**, 075011 \(2007\)](#).
- [91] L. J. Hall, D. Pinner, and J. T. Ruderman, “A Natural SUSY Higgs Near 126 GeV”, [JHEP **04**, 131 \(2012\)](#).

- [92] L. S. C. S. W. Group, *Cross sections for various subprocesses - 13 TeV*, <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>, Accessed: 2024-03-07, 2024.
- [93] ATLAS Collaboration, “SUSY August 2023 Summary Plot Update”, ATL-PHYS-PUB-2023-025 (2023).
- [94] CMS, *CMS SUS Physics Results*, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>, Accessed: 2024-03-07, 2024.
- [95] G. Aad et al. (ATLAS), “Search for long-lived charginos based on a disappearing-track signature using 136 fb⁻¹ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **82**, 606 (2022).
- [96] A. M. Sirunyan et al. (CMS), “Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **806**, 135502 (2020).
- [97] G. Aad et al. (ATLAS), “Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks in pp Collisions at $\sqrt{s}=13$ TeV with the ATLAS Detector”, *Phys. Rev. Lett.* **132**, 221801 (2024).
- [98] L. Maiani, A. D. Polosa, and V. Riquer, “Bounds to the Higgs Sector Masses in Minimal Supersymmetry from LHC Data”, *Phys. Lett. B* **724**, 274–277 (2013).
- [99] A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon, and V. Riquer, “The post-Higgs MSSM scenario: Habemus MSSM?”, *Eur. Phys. J. C* **73**, 2650 (2013).
- [100] A. Djouadi, L. Maiani, A. Polosa, J. Quevillon, and V. Riquer, “Fully covering the MSSM Higgs sector at the LHC”, *JHEP* **06**, 168 (2015).
- [101] ATLAS Collaboration, “Summary plots for beyond Standard Model Higgs boson benchmarks for direct and indirect searches”, ATL-PHYS-PUB-2022-043 (2022).
- [102] CMS, *Higgs PAG Summary Plots*, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG>, Accessed: 2024-03-11, 2024.
- [103] M. E. Gomez, G. Lazarides, and C. Pallis, “Yukawa unification, $b \rightarrow s$ gamma and Bino-Stau coannihilation”, *Phys. Lett. B* **487**, 313–320 (2000).
- [104] A. Arbey, M. Boudaud, F. Mahmoudi, and G. Robbins, “Robustness of dark matter constraints and interplay with collider searches for New Physics”, *JHEP* **11**, 132 (2017).
- [105] J. Aalbers et al. (LZ), “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment”, *Phys. Rev. Lett.* **131**, 041002 (2023).
- [106] K. Kowalska and E. M. Sessolo, “The discreet charm of higgsino dark matter - a pocket review”, *Adv. High Energy Phys.* **2018**, 6828560 (2018).
- [107] L. S. W. Group, *Combined LEP Chargino Results, up to 208 GeV for low DM*, https://lepsusy.web.cern.ch/lepsusy/www/inoslowdmsummer02/charginolowdm_pub.html, Accessed: 2024-03-13, 2024.
- [108] G. Aad et al. (ATLAS), “Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Eur. Phys. J. C* **81**, 1118 (2021).

- [109] G. Aad et al. (ATLAS), “Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **101**, 052005 (2020).
- [110] V. A. Beylin, V. I. Kuksa, G. M. Vereshkov, and R. S. Pasechnik, “Neutralino-nucleon interaction in the Split Higgsino scenario of the Dark Matter”, *Int. J. Mod. Phys. A* **24**, 6051–6069 (2009).
- [111] P. Baldi, K. Cranmer, T. Fausett, P. Sadowski, and D. Whiteson, “Parameterized neural networks for high-energy physics”, *Eur. Phys. J. C* **76**, 235 (2016).
- [112] “LHC Machine”, *JINST* **3**, edited by L. Evans and P. Bryant, S08001 (2008).
- [113] K. Aamodt et al. (ALICE), “The ALICE experiment at the CERN LHC”, *JINST* **3**, S08002 (2008).
- [114] S. Chatrchyan et al. (CMS), “The CMS Experiment at the CERN LHC”, *JINST* **3**, S08004 (2008).
- [115] A. A. Alves Jr. et al. (LHCb), “The LHCb Detector at the LHC”, *JINST* **3**, S08005 (2008).
- [116] F. Landua, “The CERN accelerator complex layout in 2022. Complexe des accélérateurs du CERN en janvier 2022”, *General Photo* (2022).
- [117] ATLAS, *Public ATLAS Luminosity Results for Run-3 of the LHC*, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3>, Accessed: 2024-03-18, 2024.
- [118] G. Aad et al. (ATLAS), “Operation and performance of the ATLAS semiconductor tracker”, *JINST* **9**, P08009 (2014).
- [119] K. Potamianos, “The upgraded Pixel detector and the commissioning of the Inner Detector tracking of the ATLAS experiment for Run-2 at the Large Hadron Collider”, *PoS EPS-HEP2015*, 261 (2015).
- [120] G. Aad et al. (ATLAS), “Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC”, *Eur. Phys. J. C* **83**, 982 (2023).
- [121] G. Avoni et al., “The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS”, *JINST* **13**, P07017 (2018).
- [122] G. Aad et al. (ATLAS), “Operation of the ATLAS trigger system in Run 2”, *JINST* **15**, P10004 (2020).
- [123] G. Aad et al. (ATLAS), “Performance of the missing transverse momentum triggers for the ATLAS detector during Run-2 data taking”, *JHEP* **08**, 080 (2020).
- [124] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. -. Shao, T. Stelzer, P. Torrielli, and M. Zaro, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07**, 079 (2014).
- [125] R. D. Ball et al., “Parton distributions with LHC data”, *Nucl. Phys. B* **867**, 244–289 (2013).
- [126] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations”, *JHEP* **03**, 015 (2013).

- [127] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191**, 159–177 (2015).
- [128] ATLAS Collaboration, “ATLAS Pythia 8 tunes to 7 TeV data”, ATL-PHYS-PUB-2014-021 (2014).
- [129] L. Lonnblad and S. Prestel, “Matching Tree-Level Matrix Elements with Interleaved Showers”, *JHEP* **03**, 019 (2012).
- [130] J. Fiaschi and M. Klasen, “Higgsino and gaugino pair production at the LHC with aNNLO+NNLL precision”, *Phys. Rev. D* **102**, 095021 (2020).
- [131] J. Fiaschi and M. Klasen, “Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II”, *Phys. Rev. D* **98**, 055014 (2018).
- [132] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV”, *JHEP* **10**, 081 (2012).
- [133] J. Debove, B. Fuks, and M. Klasen, “Joint Resummation for Gaugino Pair Production at Hadron Colliders”, *Nucl. Phys. B* **849**, 64–79 (2011).
- [134] J. Debove, B. Fuks, and M. Klasen, “Threshold resummation for gaugino pair production at hadron colliders”, *Nucl. Phys. B* **842**, 51–85 (2011).
- [135] J. Debove, B. Fuks, and M. Klasen, “Transverse-momentum resummation for gaugino-pair production at hadron colliders”, *Phys. Lett. B* **688**, 208–211 (2010).
- [136] E. Bothmann et al. (Sherpa), “Event Generation with Sherpa 2.2”, *SciPost Phys.* **7**, 034 (2019).
- [137] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11**, 040 (2004).
- [138] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11**, 070 (2007).
- [139] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06**, 043 (2010).
- [140] G. Aad et al. (ATLAS), “The ATLAS Simulation Infrastructure”, *Eur. Phys. J. C* **70**, 823–874 (2010).
- [141] S. Agostinelli et al. (GEANT4), “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506**, 250–303 (2003).
- [142] T. Cornelissen, M. Elsing, S. Fleischmann, W. Liebig, and E. Moyse, “Concepts, Design and Implementation of the ATLAS New Tracking (NEWT)”, edited by A. Salzburger (2007).
- [143] R. Fruhwirth, “Application of Kalman filtering to track and vertex fitting”, *Nucl. Instrum. Meth. A* **262**, 444–450 (1987).
- [144] ATLAS, *ATLAS Track Reconstruction – General Overview*, <https://atlassoftwaredocs.web.cern.ch/trackingTutorial/idooverview/>, Accessed: 2024-03-18, 2023.

- [145] R. Fruhwirth, W. Waltenberger, and P. Vanlaer, “Adaptive vertex fitting”, [J. Phys. G **34**, N343 \(2007\)](#).
- [146] G. Aad et al. (ATLAS), “Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1”, [Eur. Phys. J. C **77**, 490 \(2017\)](#).
- [147] M. Aaboud et al. (ATLAS), “Jet reconstruction and performance using particle flow with the ATLAS Detector”, [Eur. Phys. J. C **77**, 466 \(2017\)](#).
- [148] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, [JHEP **04**, 063 \(2008\)](#).
- [149] G. Aad et al. (ATLAS), “Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, [Eur. Phys. J. C **81**, 689 \(2021\)](#).
- [150] ATLAS Collaboration, “Tagging and suppression of pileup jets”, ATLAS-CONF-2014-018 (2014).
- [151] ATLAS Collaboration, “Optimisation and performance studies of the ATLAS b -tagging algorithms for the 2017-18 LHC run”, ATL-PHYS-PUB-2017-013 (2017).
- [152] ATLAS Collaboration, “Identification of Jets Containing b -Hadrons with Recurrent Neural Networks at the ATLAS Experiment”, ATL-PHYS-PUB-2017-003 (2017).
- [153] ATLAS Collaboration, “Secondary vertex finding for jet flavour identification with the ATLAS detector”, ATL-PHYS-PUB-2017-011 (2017).
- [154] ATLAS Collaboration, “Topological b -hadron decay reconstruction and identification of b -jets with the JetFitter package in the ATLAS experiment at the LHC”, ATL-PHYS-PUB-2018-025 (2018).
- [155] G. Aad et al. (ATLAS), “ATLAS flavour-tagging algorithms for the LHC Run 2 pp collision dataset”, [Eur. Phys. J. C **83**, 681 \(2023\)](#).
- [156] ATLAS Collaboration, “Selection of jets produced in 13TeV proton-proton collisions with the ATLAS detector”, ATLAS-CONF-2015-029 (2015).
- [157] M. Aaboud et al. (ATLAS), “Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV”, [Eur. Phys. J. C **79**, 639 \(2019\)](#).
- [158] W. Lampl, S. Laplace, D. Lelas, P. Loch, H. Ma, S. Menke, S. Rajagopalan, D. Rousseau, S. Snyder, and G. Unal, “Calorimeter clustering algorithms: Description and performance”, (2008).
- [159] ATLAS Collaboration, “Improved electron reconstruction in ATLAS using the Gaussian Sum Filter-based model for bremsstrahlung”, ATLAS-CONF-2012-047 (2012).
- [160] M. Aaboud et al. (ATLAS), “Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton-proton collision data”, [JINST **14**, P03017 \(2019\)](#).
- [161] G. Aad et al. (ATLAS), “Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment”, (2023).

- [162] G. Aad et al. (ATLAS), “Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **76**, 292 (2016).
- [163] G. Aad et al. (ATLAS), “Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **81**, 578 (2021).
- [164] M. Aaboud et al. (ATLAS), “Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **78**, 903 (2018).
- [165] F. Chollet et al., *Keras 3 api documentation*, <https://keras.io/api>, Accessed: 2024-07-01, 2024.
- [166] H. Hibi, *Search for neutralino production in final states with low transverse momentum muon in pp collision at $\sqrt{s} = 13$ TeV*, <https://hdl.handle.net/20.500.14094/D1008285>, Accessed: 2024-04-16, 2022.
- [167] M. Aaboud et al. (ATLAS), “Search for electroweak production of supersymmetric states in scenarios with compressed mass spectra at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **97**, 052010 (2018).
- [168] Y. L. Dokshitzer, “Calculation of the Structure Functions for Deep Inelastic Scattering and e^+e^- Annihilation by Perturbation Theory in Quantum Chromodynamics.”, *Sov. Phys. JETP* **46**, 641–653 (1977).
- [169] V. N. Gribov and L. N. Lipatov, “Deep inelastic $e p$ scattering in perturbation theory”, *Sov. J. Nucl. Phys.* **15**, 438–450 (1972).
- [170] G. Altarelli and G. Parisi, “Asymptotic Freedom in Parton Language”, *Nucl. Phys. B* **126**, 298–318 (1977).
- [171] M. Baak, G. J. Besjes, D. Côte, A. Koutsman, J. Lorenz, and D. Short, “HistFitter software framework for statistical data analysis”, *Eur. Phys. J. C* **75**, 153 (2015).
- [172] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71**, [Erratum: *Eur. Phys. J. C* **73**, 2501 (2013)], 1554 (2011).
- [173] A. L. Read, “Presentation of search results: The CL_s technique”, *J. Phys. G* **28**, edited by M. R. Whalley and L. Lyons, 2693–2704 (2002).
- [174] ATLAS Collaboration, “Formulae for Estimating Significance”, ATL-PHYS-PUB-2020-025 (2020).
- [175] A. Tumasyan et al. (CMS), “Search for supersymmetry in final states with two or three soft leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **04**, 091 (2022).
- [176] S. P. Martin, “Implications of purity constraints on light Higgsinos”, *Phys. Rev. D* **109**, 095045 (2024).
- [177] T. Kawamoto et al., “New Small Wheel Technical Design Report”, (2013).
- [178] ATLAS, *L1 Muon Trigger Public Results*, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1MuonTriggerPublicResults>, Accessed: 2024-06-28, 2023.

- [179] G. Aad et al. (ATLAS), “Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System”, (2013).
- [180] K. Sugizaki (ATLAS), “Integration and Commissioning of the Software-based Read-out System for ATLAS Level-1 Endcap Muon Trigger in Run 3”, [EPJ Web Conf. **251**, 04015 \(2021\)](#).