



# Constraining the 19D phenomenological Minimal Supersymmetric Standard Model with the ATLAS Experiment

Hammad Rasheed

University of Bucharest, Faculty of Physics

---

**Thesis Supervisor:** Dr. Călin Alexa, IFIN-HH, Particle Physics Department

**Committee Members:** Prof. Dr. Virgil Băran, Facultatea de Fizică, Universitatea București  
Prof. Dr. Serkant Cetin, Istinye University, Istanbul, Turkiye  
Dir. de recherche Dr. Pascal Pralavorio, CPPM/IN2P3, Marseille, France

---



# Acknowledgement

In the name of Allah, the Most Gracious, the Most Merciful. I am deeply thankful to all the people who have been a part of the physics studies and research journey, especially during my PhD. I express my gratitude to everyone who supported me during the three years of my PhD, making the process much easier and smoother. I take immense pride in having had the privilege of working with brilliant minds whose contributions made my PhD journey far more manageable than it would have been otherwise.

First and foremost, I would like to thank my supervisor, Dr. Calin Alexa, for giving me the incredible opportunity to continue my PhD within his group. I am grateful for all his help and encouragement throughout my PhD life. He always makes me independent in choosing my style of work. He always listens very carefully to me and never says no to any discussion.

Next, I would like to express my heartfelt gratitude to my advisor, Julien Maurer. I still vividly remember the early days of my PhD, when I felt like a newborn in the ATLAS Collaboration. He treated me with kindness and patience, taught me the basics, and was always available to assist me. He never hesitated to help, and his constant support motivated me at every step.

I also want to thank my second PhD advisor, Valentina Tudorache, for her unwavering support. Words are not enough to express how much I appreciate her. She helped me in every aspect, from guiding my research and suggesting directions to handling administrative tasks. She was always there to help me make decisions and provided me with the confidence I needed to succeed. Her impact on my PhD journey has been profound.

Third, I would like to acknowledge Otilia Anamaria Ducu, who has been instrumental in shaping my PhD work. She taught me so much, provided me with numerous opportunities, and guided me through my analysis work. I learned the basics of analysis under her mentorship and completed a significant portion of my research alongside her within the CTIDE group.

I am also grateful to everyone who assisted me during the first phase of my PhD when I worked on the ATLAS Qualification Task. Special thanks go to Julien Maurer again, who



supervised me during this task, making it much easier and helping to create a beautiful path forward. I would also like to thank Grigore Tarna for his assistance in validating my results and explaining the foundational concepts. I am also grateful to Sulman Younas and Bruna Pascual, who helped me understand plotting codes, and to the entire Tag and Probe team for their support in completing the qualification task within a year.

Moving on to my main PhD analysis on pMSSM, I would like to begin by thanking Brian Petersen, who was always humble, kind, and available to help me at every stage of this extensive reinterpretation of SUSY results. Biran was very proactive in answering each of my questions with nice references. I am also deeply thankful to Ben Hodkinson, whose long and detailed explanations were invaluable throughout my analysis. His support has meant a lot to me. Once again, I want to express my gratitude to my colleagues Otilia and Valentina for teaching me the basics of the frameworks in the early stages and for creating this opportunity for me to be involved in this large analysis. They never left me alone in this process. My thanks also go to Yuchen Cai, who was my fellow main analyser in this work.

I want to extend my heartfelt gratitude to my entire ATLAS IFIN team, who made me feel at home, even when I was far away from my own. A special thanks to Ioana Duminica, who helped me finish one of my analyses on monojet reinterpretation as quickly as possible. Also, when I talk about this analysis, I would like to thank Julien Maurer again. Throughout the analysis, from the initial concept, I have greatly appreciated his guidance and support. He played an important role in guiding the project and provided extensive help in reviewing the manuscript.

Outside of physics, I am grateful to my 'normal' friends who provided much-needed distractions over the last few years. There are too many to mention, but I owe a huge debt of gratitude to my school friend, Ali Raza Malik, who has always been a source of guidance and support. His invaluable advice has always been a great help to me.

I would also like to thank my family for their constant support and encouragement. It is with a heavy heart that I mention that I lost my father during my PhD journey. Dad, I know you're not physically here with me, but your lessons and prayers will always guide me. You were always the happiest person when I achieved something, and I will forever be grateful for your presence in my life. I also want to thank my beloved and caring mother and all my siblings, who have always believed in me and supported me unconditionally. I also want to express my gratitude to all my sisters-in-law, as well as my nephews and nieces, for making my holidays so enjoyable. Their love and company have always filled me with new energy, allowing me to return to work refreshed and motivated. I would also like to pay my huge thanks to my dear

uncle, Farooq Hussaini, and his family. Throughout my PhD journey, they provided me with not only their unwavering support but also the warmth of wonderful weekends that balanced my tough weekdays. Despite not having prior knowledge of the subject, they patiently listened to my physics discussions with genuine interest. Thank you so much!

Finally, I would like to express my deepest gratitude to Sania Riaz. Thank you so much for being there for me over the last five years through every high and low. Whether it was a moment of joy or sorrow, you were always by my side. Thank you for never making me feel distant from you, even when we were apart. Your listening ear, encouragement, and constant support made this journey so much easier.

# Dedication

*To my beloved parents,*  
whose unwavering love, encouragement, and sacrifices have been my constant source of  
strength.

This work is dedicated to you.

# Contents

|          |                                                                           |           |
|----------|---------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                                       | <b>1</b>  |
| <b>2</b> | <b>Theoretical foundations - from the Standard Model to Supersymmetry</b> | <b>3</b>  |
| 2.1      | The Standard Model of elementary particle physics . . . . .               | 5         |
| 2.2      | Fundamental interactions . . . . .                                        | 5         |
| 2.2.1    | Electromagnetic interaction . . . . .                                     | 6         |
| 2.2.2    | Strong interaction . . . . .                                              | 7         |
| 2.2.3    | Weak interaction . . . . .                                                | 8         |
| 2.3      | The Brout-Englert-Higgs Mechanism . . . . .                               | 10        |
| 2.4      | Limitations of the Standard Model . . . . .                               | 12        |
| 2.5      | Supersymmetry - A Beyond Standard Model Theory . . . . .                  | 14        |
| 2.5.1    | Minimal Supersymmetric Standard Model . . . . .                           | 15        |
| 2.5.2    | Supersymmetric Particles at LHC . . . . .                                 | 18        |
| 2.5.3    | Phenomenological Minimal Supersymmetric Standard Model (pMSSM) .          | 21        |
| 2.6      | Summary . . . . .                                                         | 23        |
| <b>3</b> | <b>The ATLAS experiment at the Large Hadron Collider</b>                  | <b>24</b> |
| 3.1      | The Large Hadron Collider at CERN . . . . .                               | 26        |
| 3.2      | ATLAS - A Toroidal LHC Apparatus . . . . .                                | 31        |
| 3.3      | The ATLAS Physics Program . . . . .                                       | 32        |
| 3.4      | Layers of the ATLAS Detector . . . . .                                    | 34        |
| 3.4.1    | The Inner Detector . . . . .                                              | 35        |
| 3.4.2    | Calorimeters . . . . .                                                    | 37        |
| 3.4.3    | Muon Spectrometer . . . . .                                               | 38        |
| 3.4.4    | Triggering . . . . .                                                      | 39        |
| 3.5      | Physics Objects Reconstruction . . . . .                                  | 39        |
| 3.5.1    | Initial Objects . . . . .                                                 | 40        |
| 3.5.2    | Electrons and Photons . . . . .                                           | 41        |

|          |                                                                                                                       |            |
|----------|-----------------------------------------------------------------------------------------------------------------------|------------|
| 3.5.3    | Muons . . . . .                                                                                                       | 43         |
| 3.5.4    | Jets . . . . .                                                                                                        | 44         |
| 3.5.5    | Missing transverse momentum . . . . .                                                                                 | 48         |
| 3.6      | Event generation and detector simulation . . . . .                                                                    | 49         |
| 3.7      | ATLAS Software Releases . . . . .                                                                                     | 50         |
| 3.8      | Summary . . . . .                                                                                                     | 51         |
| <b>4</b> | <b>Electron reconstruction efficiencies studies</b>                                                                   | <b>53</b>  |
| 4.1      | Context and Motivation . . . . .                                                                                      | 54         |
| 4.2      | Measurement Methodology . . . . .                                                                                     | 55         |
| 4.2.1    | Tag and probe method . . . . .                                                                                        | 56         |
| 4.2.2    | Event and Object selection . . . . .                                                                                  | 57         |
| 4.2.3    | Electron Reconstruction Efficiency . . . . .                                                                          | 58         |
| 4.2.4    | Background Evaluation . . . . .                                                                                       | 60         |
| 4.2.5    | Uncertainties . . . . .                                                                                               | 62         |
| 4.3      | Discussion on results . . . . .                                                                                       | 64         |
| 4.3.1    | Efficiency and Scale Factors measurements with ATLAS reprocessed Run<br>2 data and corresponding MC samples . . . . . | 64         |
| 4.3.2    | Efficiency and Scale Factors measurements with ATLAS early Run 3 data<br>and corresponding MC samples . . . . .       | 71         |
| 4.4      | Summary . . . . .                                                                                                     | 76         |
| <b>5</b> | <b>Fake track studies in dense environments</b>                                                                       | <b>77</b>  |
| 5.1      | Context and Motivation . . . . .                                                                                      | 78         |
| 5.2      | Fake Track Origins according to Monte Carlo Simulations . . . . .                                                     | 79         |
| 5.3      | Methodology for Measuring Fake Track Fractions in Jet Cores . . . . .                                                 | 81         |
| 5.3.1    | Event and Object Selection . . . . .                                                                                  | 83         |
| 5.3.2    | The Control Region Method . . . . .                                                                                   | 85         |
| 5.4      | Discussion on results . . . . .                                                                                       | 94         |
| 5.4.1    | Fraction of fake tracks using reprocessed Run2 Data and corresponding<br>MC Samples . . . . .                         | 94         |
| 5.4.2    | Systematic Uncertainties . . . . .                                                                                    | 97         |
| 5.5      | Summary . . . . .                                                                                                     | 99         |
| <b>6</b> | <b>A first exercise in reinterpreting search results with monojet+MET events</b>                                      | <b>101</b> |

|          |                                                                                              |            |
|----------|----------------------------------------------------------------------------------------------|------------|
| 6.1      | Context and Motivation . . . . .                                                             | 101        |
| 6.2      | General strategy . . . . .                                                                   | 102        |
| 6.3      | Discussion on Results . . . . .                                                              | 104        |
| 6.4      | Summary . . . . .                                                                            | 107        |
| <b>7</b> | <b>Interpretation of ATLAS Run II SUSY searches in the context of pMSSM</b>                  | <b>108</b> |
| 7.1      | Context and Motivation . . . . .                                                             | 109        |
| 7.2      | Methodology . . . . .                                                                        | 110        |
| 7.2.1    | Software Framework and External Constraints . . . . .                                        | 110        |
| 7.2.2    | General pMSSM Scans . . . . .                                                                | 116        |
| 7.3      | Run 2 ATLAS supersymmetric searches used for Interpretation . . . . .                        | 118        |
| 7.4      | Analysis Results . . . . .                                                                   | 120        |
| 7.4.1    | LSP Mass Constraints . . . . .                                                               | 121        |
| 7.4.2    | ATLAS constraints on the strong production side . . . . .                                    | 122        |
| 7.4.3    | ATLAS constraints on the electroweak production side . . . . .                               | 130        |
| 7.4.4    | Complementarity with Dark Matter Detection Experiments . . . . .                             | 136        |
| 7.4.5    | Complementary and Overlap of ATLAS Experiment Constraints with<br>Other Experiment . . . . . | 137        |
| 7.5      | Summary . . . . .                                                                            | 141        |
| <b>8</b> | <b>Summary and Conclusions</b>                                                               | <b>143</b> |
|          | <b>Conferences and publications related to the subject of this thesis</b>                    | <b>145</b> |
|          | <b>List of Co-Author ATLAS Publications</b>                                                  | <b>146</b> |
|          | <b>Appendices</b>                                                                            | <b>159</b> |
| <b>A</b> | <b>Additional data for Electron Reconstruction Efficiencies Studies</b>                      | <b>160</b> |
| <b>B</b> | <b>Additional data for Fake Tracks Measurements Studies</b>                                  | <b>170</b> |
| <b>C</b> | <b>Additional data for pMSSM Interpretation studies</b>                                      | <b>185</b> |
|          | <b>Acronyms</b>                                                                              | <b>198</b> |
|          | <b>Bibliography</b>                                                                          | <b>201</b> |
|          | <b>List of Figures</b>                                                                       | <b>221</b> |



# Chapter 1

## Introduction

Science seeks to understand the origins of the universe and the processes underlying its natural phenomena because of humanity’s natural curiosity. To achieve this, scientists have developed many theories throughout the ages. Creating a theory that clarifies the essential components of matter and their interactions is one of the 20th century’s most notable successes. This theory is the **Standard Model (SM)** of elementary particle physics, and it marks a critical turning point in our understanding.

However, experimental confirmation is needed to validate these theories, which is why particle accelerators are being built. The discovery of the Higgs boson in 2012 (which is a crucial particle responsible for giving masses to the elementary particles) by **A Toroidal LHC Apparatus (ATLAS)** and **Compact Muon Solenoid (CMS)** experiments at the **Large Hadron Collider (LHC)** accelerator from the **The European Organization for Nuclear Research (CERN)**. **LHC** marked a significant milestone and honoured its name among most of the accelerators built by humankind.

After achieving so much, **SM** still isn’t a complete theory, such as the tale of **Dark Matter (DM)**, the energy scale at which fundamental forces unify, and many other open questions not explained by it. Many theories can answer these questions, but some address one question while others address another. However, in this situation, **Supersymmetry (SUSY)** is a theory that can potentially answer many hidden questions all at once, and this is one of the primary subjects of this thesis.

This thesis is investigating the performance of the **ATLAS** detector and to conduct a **Beyond Standard Model (BSM)** study. We were using the Run2 data spanning from 2015 to 2018, collected by the **ATLAS** detector at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV.

Chapter 2 provides a brief introduction to the **SM** their interactions, the mechanism re-



sponsible for the massive nature of particles, and highlights the limitations encountered within the model, including **DM**. Additionally, this chapter has an introduction of **SUSY** and its minimal version, the **Minimal Supersymmetry Standard Model (MSSM)**. This chapter also gives a few details of the **phenomenological Minimal Supersymmetry Standard Model (pMSSM)**, which is the model used in this thesis, and the results are presented in chapter 7.

In Chapter 3, the experimental setup is explained in detail. The **LHC** accelerator and the **ATLAS** detector are carefully reviewed, along with the reconstruction of physics objects inside the detector.

In Chapter 4, the focus shifts to measuring electron reconstruction efficiencies with **ATLAS**'s complete **Run II** and early **Run III** data. These measurements are essential for all ongoing and future analyses.

Chapter 5 presents studies on fake track identification within the dense environment of the **ATLAS** detector, which is critical because of the very high particle density in the core of the detector. The findings from these studies can enhance the resolution of kinematics of jets in any **ATLAS** analysis.

Chapter 6 presents another **SUSY** study that expands the scope of the search for supersymmetric gluinos in events involving an intense jet and missing transverse momentum.

Chapter 7, the central part of the thesis, interprets numerous **SUSY ATLAS Run II** searches in the 19D parameter space of the **pMSSM**, including both strong and **Electroweak (EW)** production of **SUSY** particles.

Concluding remarks are provided in Chapter 8, summarizing the findings and implications of the thesis.

# Chapter 2

## Theoretical foundations - from the Standard Model to Supersymmetry

### Contents

---

|            |                                                                    |           |
|------------|--------------------------------------------------------------------|-----------|
| <b>2.1</b> | <b>The Standard Model of elementary particle physics . . . . .</b> | <b>5</b>  |
| <b>2.2</b> | <b>Fundamental interactions . . . . .</b>                          | <b>5</b>  |
| 2.2.1      | Electromagnetic interaction . . . . .                              | 6         |
| 2.2.2      | Strong interaction . . . . .                                       | 7         |
| 2.2.3      | Weak interaction . . . . .                                         | 8         |
| <b>2.3</b> | <b>The Brout-Englert-Higgs Mechanism . . . . .</b>                 | <b>10</b> |
| <b>2.4</b> | <b>Limitations of the Standard Model . . . . .</b>                 | <b>12</b> |
| <b>2.5</b> | <b>Supersymmetry - A Beyond Standard Model Theory . . . . .</b>    | <b>14</b> |
| 2.5.1      | Minimal Supersymmetric Standard Model . . . . .                    | 15        |
| 2.5.2      | Supersymmetric Particles at LHC . . . . .                          | 18        |
| 2.5.3      | Phenomenological Minimal Supersymmetric Standard Model (pMSSM)     | 21        |
| <b>2.6</b> | <b>Summary . . . . .</b>                                           | <b>23</b> |

---

For this chapter, I used the following main bibliographic sources:

- F. Halzen and A. D. Martin, “Quarks and Leptons: An introductory course in modern particle physics” [1]
- W.N. Cottingham and D.A. Greenwood, “An introduction to the standard model of particle physics” [2]
- M.E. Peskin and D.V. Schroeder “An introduction to quantum field theory” [3]
- S.P. Martin, “A supersymmetry primer” [4]
- I.J.R. Aitchison, “Supersymmetry and the MSSM: An Elementary Introduction” [5]

Numerous objects surround us; some can be observed with the naked eye, while others require microscopes and other tools. Humanity has always been curious to know the answers to specific questions, such as how the universe came into being and what the fundamental particles comprise it, ever since Plato and Aristotle. Consequently, particle physics and its research have emerged as a resource that consistently seeks to answer questions of this nature. Particle physics, sometimes called high-energy physics, studies fundamental particles and their interactions.

Since almost everything in nature is arranged in perfect order, scientists and philosophers have always attempted to create a model that would allow things to be easily described. Thus, J.J. Thompson made the initial attempt in 1897 by putting forward a model, but Japanese physicist Hantaro Nagaoka rejected it [6]. In 1911, Rutherford modified the J.J. Thompson model by proposing that “the electrons are not embedded in the nucleus, but they are revolving around it”. However, this model also has certain shortcomings, such as electron energy continuously radiating [7]. Thus, in 1913, Neil Bohr explained the atom, stating that “the electrons are orbiting the nucleus in a fixed orbit” [8].

After the efforts of various scientists and researchers over time, we have now studied the internal structure of the nucleus. But not just that, we have delved even deeper inside, meaning we have also studied the nucleons within it, namely protons and neutrons, and the collective model that knows nearly all of the information about the discovered fundamental particles (also referred to as elementary particles) known as the **SM** of particle physics by achieving a high rise in particle energies with the help of giant colliders like the **LHC**<sup>1</sup>.

However, even after this, there are still some questions that the **SM** cannot answer, such as the nature of gravity and many other unresolved inquiries. We must explore extensions **BSM** to address these questions and provide answers. In this chapter, I will introduce one such theory **SUSY**. Therefore, this chapter will cover the **SM**, its limitations, and the concept of **SUSY**

---

<sup>1</sup>Large Hadron Collider at CERN: will be explain in chapter 3

mainly concerning the experimental point of view.

## 2.1 The Standard Model of elementary particle physics

---

The **SM** of elementary particle physics [1–3] is a theory that describes the fundamental constituents of matter and their fundamental interactions. Three of the four interactions, or forces known in nature, are united in a single theoretical model: strong, **Electromagnetic (EM)** and weak. All these three interactions have associated particles called gauge/vector bosons (force-carrying particles)<sup>2</sup>. Gluons mediate the strong force, the **EM** force by photons, and in the weak force by massive  $W^\pm$  and  $Z^0$  bosons. The fourth fundamental interaction, gravity, is not included in the **SM**.

The **SM** consists of 17 elementary particles divided into two categories: fermions, spin 1/2 particles, and bosons, integer spin, 1 or 0, particles. While fermions form matter, spin 1 vector bosons are the mediators of interactions. In Table 2.1, we present a complete list of elementary particles and their characteristics: electric charge, spin, mass and the associated fundamental interactions. Leptons and quarks are two fermion subfamilies, and each of them is divided into three flavours.

## 2.2 Fundamental interactions

---

If looking at the world around us, we find that nearly all natural processes indicate some symmetry, which accounts for the universe’s order. Thus, symmetry must be introduced into a theory to be considered natural. This is why symmetry had to be added to the **SM**, and gauge theories explained the symmetry [10].

The **SM** introduces particle interactions through gauge symmetries. These symmetries determine how particles interact by exchanging force-carrying particles called gauge bosons. For example:

1. The **EM** interaction is explained by the  $U(1)$  local gauge symmetry.
2. The strong interaction is explained by the  $SU(3)$  local gauge symmetry.
3. The weak interaction is explained by the combination of  $SU(2)$  local gauge symmetries.

We will examine these fundamental interactions in more detail in the following sections.

---

<sup>2</sup>Gauge Bosons: Particle have integral spin

| Particle                            | Electric Charge ( $Q$ ) | Spin ( $s$ )  | Mass ( $\text{GeV}/c^2$ ) | Interaction      |
|-------------------------------------|-------------------------|---------------|---------------------------|------------------|
| <b>Quarks</b>                       |                         |               |                           |                  |
| Up ( $u$ )                          | $+\frac{2}{3}$          | $\frac{1}{2}$ | $\approx 0.002$           | Strong, Weak, EM |
| Down ( $d$ )                        | $-\frac{1}{3}$          | $\frac{1}{2}$ | $\approx 0.005$           | Strong, Weak, EM |
| Charm ( $c$ )                       | $+\frac{2}{3}$          | $\frac{1}{2}$ | $\approx 1.27$            | Strong, Weak, EM |
| Strange ( $s$ )                     | $-\frac{1}{3}$          | $\frac{1}{2}$ | $\approx 0.095$           | Strong, Weak, EM |
| Top ( $t$ )                         | $+\frac{2}{3}$          | $\frac{1}{2}$ | $\approx 173.1$           | Strong, Weak, EM |
| Bottom ( $b$ )                      | $-\frac{1}{3}$          | $\frac{1}{2}$ | $\approx 4.18$            | Strong, Weak, EM |
| <b>Leptons</b>                      |                         |               |                           |                  |
| Electron ( $e$ )                    | $-1$                    | $\frac{1}{2}$ | $0.511 \times 10^{-3}$    | Weak, EM         |
| Electron Neutrino ( $\nu_e$ )       | $0$                     | $0$           | $8 \times 10^{-10}$       | Weak             |
| Muon ( $\mu$ )                      | $-1$                    | $\frac{1}{2}$ | $0.106$                   | Weak, EM         |
| Muon Neutrino ( $\nu_\mu$ )         | $0$                     | $0$           | $1.9 \times 10^{-4}$      | Weak             |
| Tau ( $\tau$ )                      | $-1$                    | $\frac{1}{2}$ | $1.78$                    | Weak, EM         |
| Tau Neutrino ( $\nu_\tau$ )         | $0$                     | $0$           | $0.0182$                  | Weak             |
| <b>Gauge Bosons</b>                 |                         |               |                           |                  |
| Gluon ( $g$ )                       | $0$                     | $1$           | $0$                       | Strong           |
| Photon ( $\gamma$ )                 | $0$                     | $1$           | $0$                       | EM               |
| Z Boson ( $Z^0$ )                   | $0$                     | $1$           | $91.2$                    | Weak             |
| W Bosons ( $W^\pm$ )                | $\pm 1$                 | $1$           | $80.4$                    | Weak             |
| <b>Scalar Boson</b>                 |                         |               |                           |                  |
| <b>Higgs boson (<math>H</math>)</b> | $0$                     | $0$           | $\approx 125$             |                  |

Table 2.1: Fundamental building blocks in the domain of Elementary Particle Physics that correspond to the Standard Model [9].

### 2.2.1 Electromagnetic interaction

**EM** interaction governs the forces between charged particles. It specifically influences particles with an electric charge, such as electrons and muons, through the exchange of massless photons, which mediate this force. This force has an infinite range, meaning it can act over large distances, but its strength gets weaker as the distance increases. **Quantum Electrodynamics (QED)** is the theory that explains how electrically charged particles interact by exchanging photons. The **QED** Lagrangian develops by first introducing the Lagrangian of free massive fermion:

$$\mathcal{L}_{Dirac}(x) = \bar{\psi}(x)(i\gamma^\mu\partial_\mu - m)\psi(x) \quad (2.1)$$

Where  $\psi(x)$  is the fermionic field,  $\gamma^\mu$  are Dirac matrices, and  $m$  is the fermion's mass. This Lagrangian should be invariant under the local gauge transformation, which is given by

$$\psi(x) \rightarrow \Psi'(x) = e^{-ie\alpha(x)}\psi(x) \quad (2.2)$$

The gauge field  $A_\mu(x)$  (a photonic field) transforms as follows

$$A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x) \quad (2.3)$$

and the covariant derivative is given by

$$D_\mu = \partial_\mu + ieA_\mu \quad (2.4)$$

where  $e$  is the electric charge of fermions called the coupling constant of weak interaction. Now, the complete Lagrangian is given as

$$\mathcal{L}_{QED}(x) = \bar{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x) - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x) \quad (2.5)$$

where  $F^{\mu\nu} = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$  called **EM** field tensor. The **QED** Lagrangian includes the kinematic terms for the Dirac field, the free **EM** field, and the interaction between fermions and the **EM** field.

### 2.2.2 Strong interaction

The strong interaction is the force that keeps protons and neutrons tightly packed together inside the nucleus of an atom. Massless gluons carry this force. These gluons interact with quarks inside protons and neutrons. The range of the strong interaction is very short, working only at distances similar to the size of an atomic nucleus (around  $10^{-15}$  meters). **Quantum Chromodynamics (QCD)** is a gauge theory that handles the dynamic relationship between quarks and gluons. The **QCD** Lagrangian develops by first introducing the free Lagrangian for quarks:

$$\mathcal{L} = \bar{q}(x)(i\gamma^\mu\partial_\mu - m)q(x) \quad (2.6)$$

This Lagrangian should be invariant under local transformation as

$$q(x) \rightarrow q'(x) = e^{i\alpha_a(x)\frac{\lambda_a}{2}}q(x) \quad (2.7)$$

where  $\alpha_a(x)$  is the arbitrary local parameter and  $\lambda_a$  are the Gell-Mann matrices with  $a = 1, 2, \dots, 7, 8$  [3]. Now, similar to **QED** for the invariance of this Lagrangian, we also need to introduce eight gauge fields  $G_\mu^a(x)$ , which are the gluon fields transformed as

$$G_\mu^a(x) \rightarrow G_\mu'^a(x) = G_\mu^a(x) - \frac{1}{g_s} \partial_\mu \alpha_a(x) - f^{abc} \alpha_b(x) G_{c\mu}(x) \quad (2.8)$$

and the covariant derivative is given by

$$D_\mu = \partial_\mu + g_s T^a G_\mu^a \quad (2.9)$$

where  $g_s$  is the coupling constant of strong interaction. Now, the complete Lagrangian is given as

$$\mathcal{L}_{QCD}(x) = \bar{q}(x)(i\gamma^\mu D_\mu - m)q(x) - \frac{1}{4} G_{\mu\nu}^a(x) G_a^{\mu\nu}(x) \quad (2.10)$$

where  $G_{\mu\nu}^a = \partial_\mu G_\nu^a(x) - \partial_\nu G_\mu^a(x) - g_s f^{abc} G_{b\mu} G_{c\nu}$  called gluon field tensor. Overall, the **QCD** Lagrangian includes the kinematic terms for the free Dirac Lagrangian of quarks, the free Lagrangian for the gluon fields, the interaction term between quarks and gluons, and the interaction term between gluons themselves.

### 2.2.3 Weak interaction

The weak interaction is responsible for processes that involve the decay of fundamental particles, where one type of particle transforms into another. The weak interaction is mediated by three massive spin 1 vector bosons  $W^+$ ,  $W^-$ , and  $Z^0$ . The weak interaction operates over an extremely short range, typically on the order of  $10^{-18}$  meters. The weak interaction is considerably weaker than both the **EM** and strong interactions. This interaction is introduced in the **SM** Lagrangian, imposing a local  $SU(2)$  symmetry on the Dirac Lagrangian. To derive the weak interaction Lagrangian, we begin with the free Dirac Lagrangian, as also in case **QED**:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}(x) (i\gamma^\mu \partial_\mu - m) \psi(x) \quad (2.11)$$

The weak interaction is based on the  $SU(2)_L$  gauge symmetry, where left-handed fermions are grouped into doublets. For example:

$$\psi_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L \quad (2.12)$$

The Lagrangian must be invariant under a local gauge transformation:

$$\psi_L(x) \rightarrow \psi'_L(x) = e^{-i\alpha_a(x)\frac{\tau_a}{2}} \psi_L(x) \quad (2.13)$$

where  $\alpha_a(x)$  are the gauge parameters and  $\tau_a$  are the Pauli matrices. To ensure gauge invariance, we introduce the covariant derivative:

$$D_\mu = \partial_\mu + ig\frac{\tau_a}{2}W_\mu^a \quad (2.14)$$

where  $g$  is the coupling constant of the weak interaction, and  $W_\mu^a$  are the gauge boson fields, with  $a = 1, 2, 3$  corresponding to the weak gauge bosons  $W_\mu^1$ ,  $W_\mu^2$ , and  $W_\mu^3$ . Now, the complete lagrangian is given as:

$$\mathcal{L}_{\text{Weak}} = \bar{\psi}_L(x)\gamma^\mu \left( i\partial_\mu - g\frac{\tau_a}{2}W_\mu^a \right) \psi_L(x) - \frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu} \quad (2.15)$$

where  $W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g\epsilon^{abc}W_\mu^b W_\nu^c$ . Overall, the weak interaction Lagrangian describes both the interaction between left-handed fermions and the weak gauge bosons and the self-interactions of the gauge bosons themselves.

## Electroweak interaction

In **SM**, the weak and **EM** forces, although they appear different, are two aspects of a single unified force known as the **EW** interaction. This unification is based on a symmetry group called  $SU(2)_L \otimes U(1)_Y$ . The **EW** theory was proposed by Sheldon Glashow, Abdul Salam, and Steven Weinberg to combine **EM** and weak interaction [11–13]. In the **EW** theory, left-handed fermions are grouped as doublets with weak isospin  $T = 1/2$ , while right-handed fermions are singlets::

$$X_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L, \begin{pmatrix} q^u \\ q^d \end{pmatrix}_L \quad (2.16)$$

$$\psi_R = \ell_R, q_R^u, q_R^d \quad (2.17)$$

where  $\ell$  represents charged leptons,  $\nu_\ell$  refers to their corresponding neutrinos, and  $q^{u,d}$  stands for up-type and down-type quarks. Similar to the other theories, the Lagrangian regarding this theory is also required to be invariant under local transformations of  $SU(2)_L \otimes U(1)_Y$ , which transform the fields as:

$$X_L(x) \rightarrow X'_L = e^{i\beta(x)Y + i\alpha^a(x)\frac{\sigma_a}{2}} X_L(x) \quad (2.18)$$



$$\psi_R(x) \rightarrow \psi'_R = e^{i\beta(x)Y} \psi_R(x) \quad (2.19)$$

where  $\alpha(x)$  and  $\beta(x)$  are phase transformation factors of the aforementioned groups respectively and  $\sigma_a$  represents Pauli matrices with  $a=1,2,3$ . Now, similar to other theories, the derivative is replaced with covariant derivative as :

$$D_\mu = \partial_\mu + igW_\mu^a \frac{\sigma_a}{2} + ig'B_\mu Y \quad (2.20)$$

where  $W_\mu^a$  ( $a = 1, 2, 3$ ) and  $B_\mu$  are gauge fields of  $SU(2)_L$  and  $U(1)_Y$ , with  $g$  and  $g'$  being the coupling constants.

Overall, the complete Lagrangian regarding **EW** theory is given below where  $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

$$\begin{aligned} \mathcal{L}_{EW}(x) = & \bar{X}_L(x) \gamma^\mu \left( i\partial_\mu - g \frac{\tau_a}{2} W_\mu^a + \frac{g'}{2} B_\mu \right) X_L(x) \\ & + \bar{\psi}_R(x) \gamma^\mu (i\partial_\mu + g' B_\mu) \psi_R(x) - \frac{1}{4} W_{\mu\nu}^a(x) W_a^{\mu\nu}(x) - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \end{aligned} \quad (2.21)$$

## 2.3 The Brout-Englert-Higgs Mechanism

---

The Higgs mechanism resolves the mystery of how fundamental particles acquire mass [14–16], originally proposed by Peter Higgs, François Englert, Robert Brout. To introduce this mechanism, the gauge symmetry needs to be preserved, which implies that the masses of gauge bosons are supposed to be massless. However, masses of all these particles have been measured, indicating that symmetry in the **SM** must somehow be broken. The solution to this lies in the Higgs mechanism, which introduces an iso-spin doublet of complex scalar fields  $\phi$  that generates masses through spontaneous symmetry breaking. If one starts with the Lagrangian of the Higgs,

$$\mathcal{L} = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi) \quad (2.22)$$

where  $\phi$  can be illustrated as

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

and  $D_\mu$  is the covariant derivative when operating at scalar Higgs field given as

$$D_\mu \phi = \left( \partial_\mu - ig \frac{\tau}{2} * \omega_\mu - ig' \frac{Y}{2} B_\mu \right) \phi \quad (2.23)$$

and similarly, its corresponding complex term is given as

$$D_\mu \phi^\dagger = \left( \partial_\mu + ig \frac{\tau}{2} * \omega_\mu + ig' \frac{Y}{2} B_\mu \right) \phi^\dagger \quad (2.24)$$

in both of the above equations,  $g'$  and  $g$  are the coupling constants associated with U(1) and SU(2) gauge groups respectively,  $\tau$  are the Pauli matrices with SU(2) gauge group,  $B_\mu$  and  $W_\mu$  are the gauge fields corresponding to U(1) and SU(2) gauge groups respectively, and  $Y$  is the weak hypercharge of the Higgs field. Now the gauge invariant potential term  $V(\phi)$  defined as

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

where  $\mu^2$  a real constant is the mass parameter associated with the Higgs scalar field, which is less than zero, and  $\lambda$  is the self-coupling parameter of the Higgs scalar field, greater than zero. For +ve and real  $\mu^2$  and  $\lambda$ , this potential is a *Mexican hat*. It has an infinite number of minima at a non-zero value  $\phi^\dagger \phi = \frac{|u|}{\lambda} = \nu$  where  $\nu$  denotes the vacuum expectation value, which is nearly equal to 246 GeV. The Higgs field can now be extended around the minimum  $\nu$ :

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.25)$$

where  $h(x)$  is the perturbative expansion referred to as the field associated with the Higgs boson. The gauge boson masses are produced by inserting equation 2.23, 2.24, 2.25 in the first term of equation 2.22 yields:

$$(D^\mu \phi)^\dagger D_\mu \phi = \frac{v^2}{8} \left[ g^2 (W_\mu^1)^2 + (W_\mu^2)^2 + (gW_\mu^3 - g'B_\mu)^2 \right] \quad (2.26)$$

Then, the following linear combinations defined the weak boson in the **EW** theory:

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2) \quad \text{with } m_W = \frac{g\nu}{2} \quad (2.27)$$

$$Z_\mu = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \quad \text{with } m_Z = \frac{\nu}{2} \sqrt{g^2 + g'^2} \quad (2.28)$$

$$A_\mu = \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \quad \text{with } m_A = 0 \quad (2.29)$$

We can obtain the Higgs boson mass as:

$$m_h^2 = 2\mu^2 = 2\lambda\nu \quad (2.30)$$

The weak mixing angle is denoted by  $\theta_w$ . It is connected to the **EW** coupling constants and the masses of the W and Z bosons by

$$\cos\theta_w = \frac{m_W}{m_Z} = \frac{g'}{\sqrt{g^2 + g'^2}} \quad \sin\theta_w = \frac{g}{\sqrt{g^2 + g'^2}} \quad (2.31)$$

## 2.4 Limitations of the Standard Model

---

As illustrated in the sections above, the **SM** is a successful theoretical framework. Its capacity to clarify the behaviour of fundamental particles and interactions indicates its success. But despite all of its accomplishments, the **SM** still has a lot of problems. A significant obstacle in the model is its multiple free parameters, roughly between 19 and 26. In addition to that, the **SM** encountered numerous other difficulties, a few of which are listed below:

1. **Gravity:** The fundamental force of gravity is not explained by the **SM** because it only relies on those field theories based on quantum mechanics.
2. **Massive observation of neutrinos:** Neutrinos were believed to have no mass when the **SM** was created. However, subsequent observations of their oscillations at accelerators show they have mass [17, 18]. This finding reveals a gap in the **SM**, indicating the need to include neutrino masses in the model.
3. **Asymmetry of matter and anti-matter:** The **SM** also does not explain the large Asymmetry of particles (matter) and anti-particles (anti-matter) [19].
4. **Grand unification:** The absence of unification of the three gauge interactions, **EM**, weak, and strong, is another drawback of the **SM** [20].

In recent decades, the establishment of these postulates has given the motivation to study physics beyond the **SM** and to express the problems with the **SM**. For example, **Grand Unification Theory (GUT)** and string theory convey that there is a single, universal source for all elementary interactions. Realisation of **EW** scale **SUSY** like **MSSM** and **Constrained Minimal Supersymmetric Standard Model (cMSSM)** are the motivation for a possible explanation of **DM** and Hierarchy problems in the **SM**. These two problems are briefly outlined in the following two sections.

### Dark Matter

The existence of **DM**, which is non-luminous and non-absorbing, is now widely accepted [21]. The orbital speeds of stars in galaxies can't be explained without **DM** [22]. The **DM** hypothesis

suggests that this matter only interacts through gravity and the weak nuclear force, as it does not carry any electric or colour charges [23–26]. Measurements of the cosmic microwave background by the Planck Collaboration provide evidence for the  $\Lambda$  cold dark matter model [27]. According to these measurements:

$$\Omega_b = 0.02237 \pm 0.00015$$

$$\Omega_c = 0.1200 \pm 0.0012$$

These values indicate that dark matter makes up 27% of the universe’s energy density, while baryonic matter, described by the **SM**, accounts for only 5%. The remaining 68% of the universe’s energy is considered dark energy, which drives the universe’s expansion. Several theories are put forward to address the **DM** mystery, such as the existence of **Weakly Interacting Massive Particles (WIMPs)** is one of the most motivated candidates, which couple to the **EM** interaction only very weakly, interact with gravity, and have the proper relic density—all of which are necessary for a **DM** candidate. The relationship between **WIMPs** and other elementary particles suggests that **WIMPs** might have continued to annihilate into **SM** particles rather than decaying. In an aspect of **SUSY**, the **Lightest Supersymmetric Particle (LSP)**, named neutralino, is neutral and stable in many **SUSY** models with exact R-parity conservation, and it may be a good candidate for **DM**.

## Hierarchy problem

The large discrepancy between the Planck scale (the energy scale at which quantum gravitational effects become significant) of about  $10^{19}$  GeV and the weak scale (characterized by the mediators of the weak force) of about 100 GeV is known as the Hierarchy Problem, a fundamental problem in particle physics. The vast difference in scaling inspires inquiries regarding the reliability of the **SM** of elementary particle physics. The significance of the Hierarchy Problem increases when one considers the quantum corrections to the Higgs boson mass.

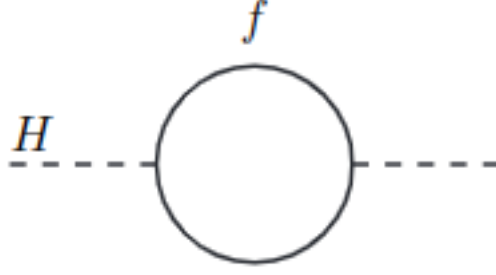


Figure 2.1: Loop Feynman diagram example which corrects Higgs mass [4]

If we consider the Higgs boson of the **SM**, radiative corrections from loop diagrams, like the example shown in Figure 2.1, affect the square of the Higgs boson mass. The coupling of fermions with the Higgs boson leads to a quantum correction, described by the equation:

$$\Delta m_{Higgs}^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 \quad (2.32)$$

Here,  $\lambda_f$  is the Yukawa coupling of the fermions, and  $\Lambda_{UV}$  is the ultraviolet momentum cutoff used to regulate the loop integral of the theory, which is the Planck mass in the **SM** [4]. One suggested resolution to this problem is **SUSY**, which postulates a relationship between fermions and bosons. In this framework, every fermion would have a bosonic counterpart of the same mass, and similarly, each boson would be paired with a fermion of equal mass. In this case, all radiative corrections would cancel each other out [28, 29].

## 2.5 Supersymmetry - A Beyond Standard Model Theory

**SUSY** [5, 30–35], if experimentally confirmed then will become the base model for the elementary particle physics. According to this theoretical framework, nearly all questions that the **SM** struggles to answer find resolution. In basic terms, **SUSY** argues that for every particle in the **SM**, there exists a partner particle known as a superpartner, differing in spin half. For instance, fermions in the **SM** are associated with new bosons in **SUSY**.

The comparison of the **SM** particles and their superpartners is shown in Table 2.2. The quarks and leptons in the **SM** correspond to the squarks and sleptons in **SUSY**. Additionally, gauginos are the superpartners of the gauge bosons. Furthermore, **SUSY** introduces a new quantum number called R-parity [36, 37]. According to R-parity conservation, **SM** particles have even R-parity values, while their superpartners carry odd R-parity values. R-parity can

be expressed as

$$R_{\text{parity}} = (-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{for } \mathbf{SM} \text{ particles} \\ -1 & \text{for } \mathbf{SUSY} \text{ particles} \end{cases} \quad (2.33)$$

where  $B$ ,  $L$ , and  $s$  are Baryon number<sup>3</sup>, Lepton number<sup>4</sup>, and spin of the particles respectively. One key consequence of R-parity conservation is that **SUSY** particles must always be produced in pairs at the **LHC**. This means that individual **SUSY** particles cannot be created alone, which influences the type of particle interactions and events that can be observed experimentally. Separately, another important outcome of R-parity conservation is that the **LSP** must be stable, as it cannot decay into **SM** particles. This stability allows the **LSP** to evade the detector without leaving a visible signal, which provides a distinct signature for **SUSY** events and enables a clear distinction between **SM** background and **SUSY** processes.

| Particle            | SM Spin       | SUSY Particle               | SUSY Spin     |
|---------------------|---------------|-----------------------------|---------------|
| Quarks ( $q$ )      | $\frac{1}{2}$ | Squarks ( $\tilde{q}$ )     | 0             |
| Leptons ( $\ell$ )  | $\frac{1}{2}$ | Sleptons ( $\tilde{\ell}$ ) | 0             |
| Higgs boson ( $H$ ) | 0             | Higgsino ( $\tilde{H}$ )    | $\frac{1}{2}$ |
| Gauge bosons        | 1             | Gauginos                    | $\frac{1}{2}$ |

Table 2.2: Comparison of the SM particles with their Supersymmetric partners concerning their spins.

### 2.5.1 Minimal Supersymmetric Standard Model

**SUSY** is a big framework and **MSSM** is the model that includes the smallest number of new fields to properly extend the full **SM**[\[4, 5\]](#). In the context of the **MSSM**, the superpartners of the **EW** interaction gauge bosons are referred to as Binos ( $\tilde{B}$ ) and Winos ( $\tilde{W}$ ), while the superpartner of the gluon in the strong interaction is called the gluino ( $\tilde{g}$ ).

---

<sup>3</sup>Baryon number: Quantum number that indicates the total number of baryons

<sup>4</sup>Lepton number: Quantum number that indicates the total number of leptons

| Names               | Gauge eigenstates                                        | Mass eigenstates                                                         | R-parity | Spin          |
|---------------------|----------------------------------------------------------|--------------------------------------------------------------------------|----------|---------------|
| <b>Higgs Bosons</b> | $H_u^0 \ H_d^0 \ H_+^0 \ H_d^-$                          | $h^0 \ H^0 \ A^0 \ H^\pm$                                                | +1       | 0             |
| <b>squarks</b>      | $\tilde{u}_L \ \tilde{d}_L \ \tilde{u}_R \ \tilde{d}_R$  | same                                                                     | −1       | 0             |
|                     | $\tilde{s}_L, \tilde{c}_L \ \tilde{s}_R \ \tilde{c}_R$   | same                                                                     |          |               |
|                     | $\tilde{t}_L \ \tilde{b}_L \ \tilde{t}_R \ \tilde{b}_R$  | $\tilde{t}_1 \ \tilde{t}_2 \ \tilde{b}_1 \ \tilde{b}_2$                  |          |               |
| <b>sleptons</b>     | $\tilde{e}_L \ \tilde{e}_R \ \tilde{\nu}_e$              | same                                                                     | −1       | 0             |
|                     | $\tilde{\mu}_L \ \tilde{\mu}_R \ \tilde{\nu}_\mu$        | same                                                                     |          |               |
|                     | $\tilde{\tau}_L \ \tilde{\tau}_R \ \tilde{\nu}_\tau$     | $\tilde{\tau}_1 \ \tilde{\tau}_2 \ \tilde{\nu}_\tau$                     |          |               |
| <b>neutralinos</b>  | $\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$ | $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ | −1       | $\frac{1}{2}$ |
| <b>charginos</b>    | $\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{H}_d^\pm$        | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$                                 | −1       | $\frac{1}{2}$ |
| <b>gluino</b>       | $\tilde{g}$                                              | same                                                                     | −1       | $\frac{1}{2}$ |

Table 2.3: Particles introduced by the MSSM, except  $h^0$ , are shown in terms of their gauge and mass eigenstates. The gauge eigenstates refer to the particle states before electroweak symmetry breaking, while the mass eigenstates correspond to the physical particles after electroweak symmetry breaking.

The **Higgs sector in MSSM** is defined in a more complex manner compared to the simple approach in the **SM**. Unlike in the **SM**, where a single Higgs doublet is sufficient to give mass to particles, two Higgs doublets are required in **MSSM**, denoted as  $H_u$  and  $H_d$ . These Higgs doublets are responsible for providing mass to up-type quarks, down-type quarks, and leptons separately. Each of these Higgs doublets has two weak isospin components, expressed as:

$$(H_u^+ H_u^0), (H_d^0 H_d^-)$$

The corresponding superpartners are called higgsinos and are denoted similarly with a tilde sign as:

$$(\tilde{H}_u^+ \tilde{H}_u^0), (\tilde{H}_d^0 \tilde{H}_d^-)$$

In **MSSM**, each Higgs doublet has its vacuum expectation value  $\nu_u$  and  $\nu_d$ , related to the vacuum expectation value of the Higgs in the **SM** through:

$$\nu = \sqrt{\nu_u^2 + \nu_d^2} \quad (2.34)$$

a specific parameter, often denoted as

$$\tan\beta = \frac{\nu_u^2}{\nu_d^2}$$

Which is a parameter of the **pMSSM** explained in section 2.5.3. A fact about this model is that with two complex doublets, **MSSM** introduces 8 degrees of freedom. Three of these degrees of freedom are used to give masses to the W and Z bosons, leaving behind five physical Higgs bosons: one CP-odd scalar Higgs denoted as  $A^0$ , two CP-even scalar Higgs denoted as  $h^0$  and  $H^0$ , and two oppositely charged scalar Higgs denoted as  $H^\pm$ .

Particles in the **MSSM** model are introduced as chiral supermultiplets and gauge supermultiplets. They are initially defined in terms of fields before the **EW** symmetry breaking and later transformed into mass eigenstates. Sleptons ( $\tilde{\ell}$ ) as well as squarks ( $\tilde{q}$ ) can experience mixing between their left-handed (L) and right-handed (R) states. The first and second-generation squarks ( $\tilde{q}$ ) and sleptons ( $\tilde{\ell}$ ) are assumed to be in seven almost mass-degenerate separated pairs identified as:

$$(\tilde{u}_R, \tilde{c}_R), (\tilde{d}_R, \tilde{s}_R), (\tilde{u}_L, \tilde{c}_L), (\tilde{d}_L, \tilde{s}_L), (\tilde{e}_R, \tilde{\mu}_R), (\tilde{\nu}_e, \tilde{\nu}_\mu), (\tilde{e}_L, \tilde{\mu}_L) \quad (2.35)$$

On the other hand, the third generation's squarks and sleptons combine to form the mass eigenstates, such as  $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{\tau}_1$ , and  $\tilde{\tau}_2$ . Similarly, other superpartners, such as charged winos, binos, and higgsinos, mix to form charginos labelled as  $\tilde{\chi}_1^+, \tilde{\chi}_2^+$  and neutralinos  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ . Gluinos, however, do not mix with any other particles, which makes them unique. The both field content and corresponding mass eigenstates of particles in **MSSM** are given in Table 2.3. **SUSY** imposes that the masses of its particles be around the masses of the **SM** particles. Currently, no **SUSY** particle has been discovered, which suggests that **SUSY** particles must be significantly heavier than their **SM** counterparts, implying that **SUSY** is broken. This breaking must occur in a controlled manner to avoid reintroducing the hierarchy problem, and this is where the concept of 'soft' **SUSY** breaking comes in. Although a specific mechanism for **SUSY** breaking has not yet been established, several models have been proposed. In **Minimal Supergravity (mSUGRA)**, **SUSY** breaks via gravitational interactions, while in **Gauge-Mediated Supersymmetry Breaking (GMSB)**, gauge interactions mediate the breaking. Another well-known mechanism is **Anomaly-Mediated Supersymmetry Breaking (AMSB)**, in which **SUSY** breaking occurs due to anomalies in the theory's gauge symmetries [38]. As a result of soft **SUSY** breaking in the **MSSM**, the model acquires over



100 additional parameters [39].

### 2.5.2 Supersymmetric Particles at LHC

The **LHC** can observe the existence of **SUSY** in various ways, such as through the masses of sparticles or the branching ratios of certain decays. As explained in section 2.5, if R-parity is conserved, **SUSY** particles will

be produced in pairs, and the **LSP**, often referred to as the neutralino  $\tilde{\chi}_1^0$ , will be stable. Additionally, the decay of these **SUSY** particles will typically result in the production of at least one **SM** particle alongside the  $\tilde{\chi}_1^0$ , which remains stable. Different experiments at the **LHC** [41] have already placed limits on the presence of particles where on coloured particles<sup>5</sup> it is beyond TeV while on **Electroweakino (EWkino)**<sup>6</sup> is

much weaker [42–44]. By referring to figure 2.2, which represents the cross-sections of various processes involving sparticles at  $\sqrt{s} = 13$  TeV, it becomes evident that processes involving sparticles interacting via strong interactions have higher cross-sections compared to those involving **EWkinos**. One reason for this higher cross-section of strong particles is their strong coupling. Overall, any chain of **SUSY** decay culminates with the neutralino, which is associated with missing transverse energy, an observable in **LHC** experiments.

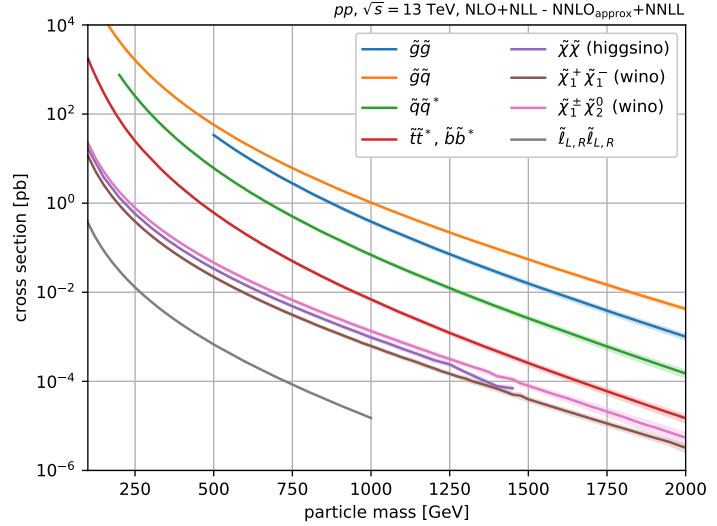


Figure 2.2: SUSY processes cross-section at  $\sqrt{s} = 13$  TeV [40]

#### Strong sector of Supersymmetry at LHC:

For both squarks and gluinos, if  $m_{\tilde{q}} \ll m_{\tilde{g}}$ , the production of  $\tilde{q}$  is easier to observe. Conversely, if  $m_{\tilde{g}} \ll m_{\tilde{q}}$ , the production of  $\tilde{g}$  is easier to detect.

For gluinos:

- if they are heavier, the dominant decay modes are:  $\tilde{g} \rightarrow q\bar{q}\tilde{q}$  ;  $\tilde{g} \rightarrow q\bar{q}$
- if they are lighter, the dominant decay modes are:  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0$  ;  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^\pm$

<sup>5</sup>Coloured particles involves squarks and gluinos.

<sup>6</sup>Neutralinos and Charginos combinely called electroweakinos.

For squarks: the dominant decay mode is  $\tilde{q} \rightarrow q\tilde{g}$  while if it is not possible, then it decays like:

$$\tilde{q} \rightarrow q\tilde{\chi}^0 \quad ; \quad \tilde{q} \rightarrow \bar{q}\tilde{\chi}^\pm$$

Typical production mechanisms for squarks and gluinos at the **LHC** are depicted through Feynman diagrams in Figure 2.3.

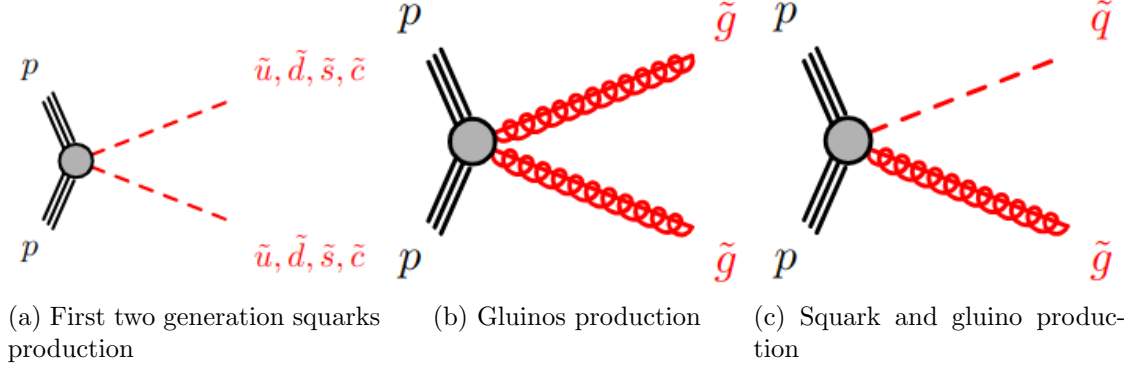


Figure 2.3: Strong production of SUSY at LHC

### Electroweak sector of Supersymmetry at LHC:

- Sleptons are decay into their partner **SM** lepton in addition to Charginos or Neutralinos. 2-body sleptons decays are

$$\tilde{\nu} \rightarrow \nu + \tilde{\chi}^0 \quad ; \quad \tilde{\nu} \rightarrow \ell + \tilde{\chi}^\pm \tilde{\ell} \rightarrow \nu + \tilde{\chi}^\pm \quad ; \quad \tilde{\ell} \rightarrow \ell + \tilde{\chi}^0 \quad ;$$

The decay with  $\tilde{\chi}^0 = \tilde{\chi}_1^0$  is always allowed kinematically, while other decays are important if  $\tilde{\ell}$  are heavy enough.

- Since each Neutralinos and Charginos has coupling from the bino and Wino fields in addition to additional couplings from the gaugino-gaugino-vector and gaugino-higgsino-higgs, the common 2-body decay modes involve:

$$\tilde{\chi}^0 \rightarrow Z\tilde{\chi}^0 \quad ; \quad \tilde{\chi}^0 \rightarrow h^0\tilde{\chi}^0 \quad ; \quad \tilde{\chi}^0 \rightarrow W\tilde{\chi}^\pm \quad ; \quad \tilde{\chi}^0 \rightarrow \nu\tilde{\nu} \quad ; \quad \tilde{\chi}^0 \rightarrow \ell\tilde{\ell} \quad ; \quad \tilde{\chi}^0 \rightarrow q\tilde{q}$$

$$\tilde{\chi}^\pm \rightarrow Z\tilde{\chi}_1^\pm \quad ; \quad \tilde{\chi}^\pm \rightarrow h^0\tilde{\chi}_1^\pm \quad ; \quad \tilde{\chi}^\pm \rightarrow W\tilde{\chi}^0 \quad ; \quad \tilde{\chi}^\pm \rightarrow \nu\tilde{\ell} \quad ; \quad \tilde{\chi}^\pm \rightarrow \ell\tilde{\nu} \quad ; \quad \tilde{\chi}^\pm \rightarrow q\tilde{q}$$

the decay channels are also possible with other Higgs as  $A^0$ ,  $H^0$ ,  $H^\pm$ .

A few examples of the initial production of sleptons and **EWkino** at **LHC** in the form of Feynman diagrams are shown in Figure 2.4.

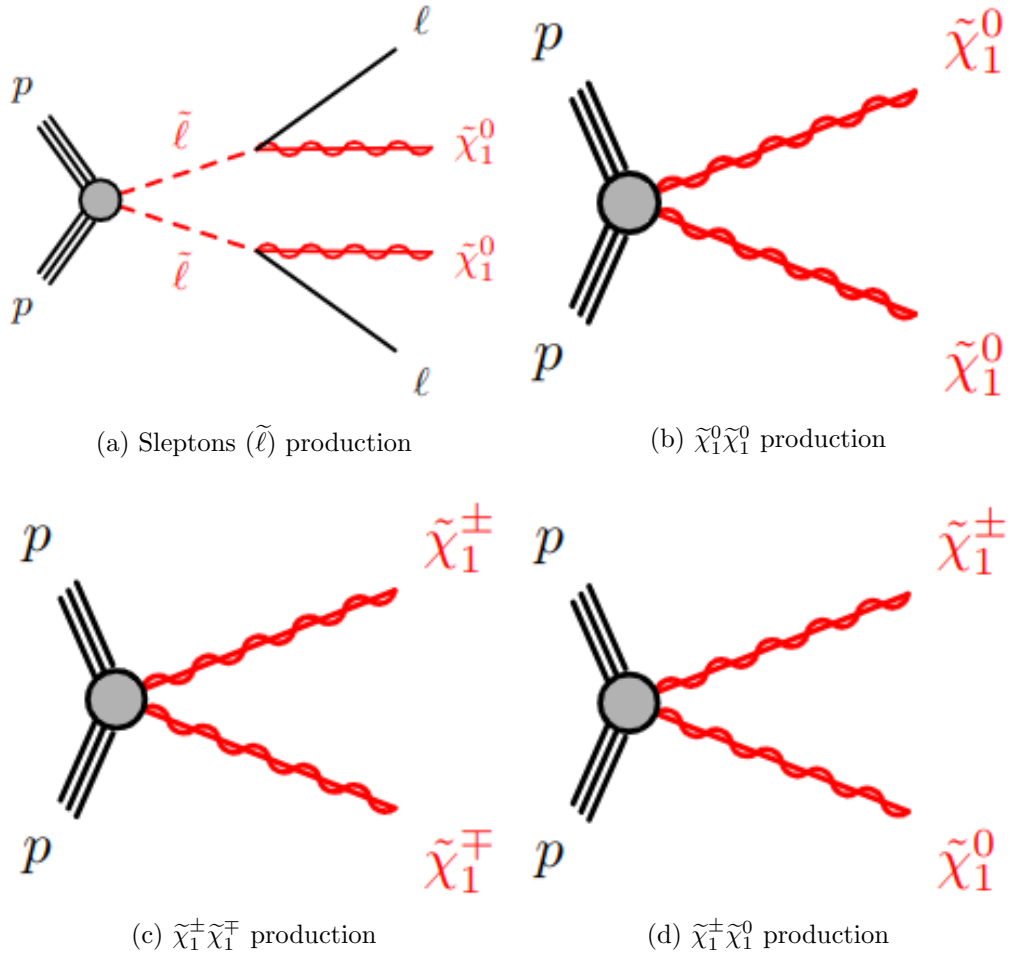


Figure 2.4: Electroweak production of SUSY at LHC

### 2.5.3 Phenomenological Minimal Supersymmetric Standard Model (pMSSM)

In **MSSM**, there are many free parameters, making it challenging to scan them all and compare them with data simultaneously. This complexity presents difficulties in conducting **SUSY** searches at the **LHC**. Consequently, in **LHC** experiments, those models are utilized that depend on a few parameters, such as **Simplified Models** [45], which reduce the complexity of **MSSM**. Their main objective is to set limits on sparticles in the context of several **SUSY** searches. Simplified models present a two-dimensional plot where one axis represents a possible sparticle, while the other axis represents the stable particle (neutralino), as depicted in Figure 2.5.

Some sparticles and their possible decay channels are considered in these models, while the rest are assumed to be decoupled. Branching fractions in simplified models are either 100% or 0%. In simplified models, ewkinos are purely Wino, Bino, or Higgsino. However, simplified models' oversimplification is a drawback, highlighting the importance of interpreting **SUSY** searches in a more general **SUSY** model. The pathway for reinterpreting **SUSY** searches lies between simplified models, and **MSSM** is possible with the **pMSSM** [47] (the model used in this thesis to reinterpret **SUSY** searches).

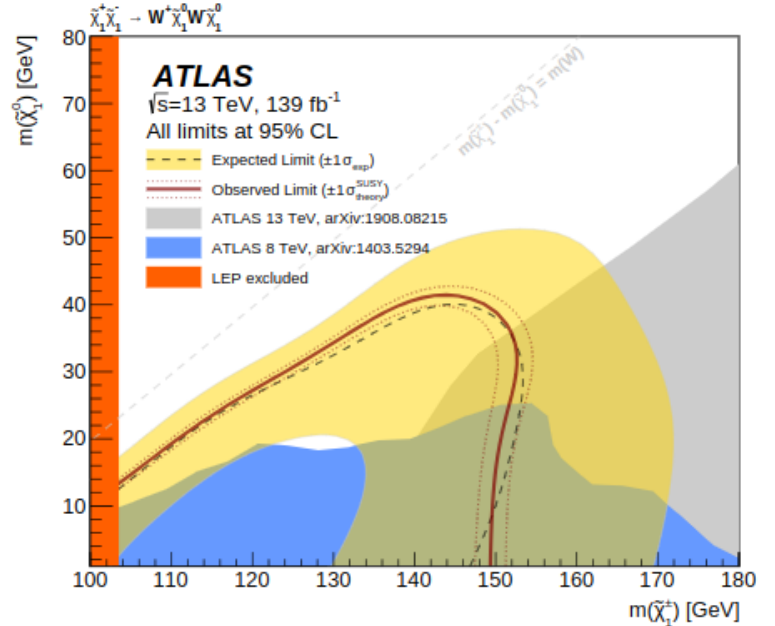


Figure 2.5: Observed and expected exclusion limits on SUSY simplified models for chargino-pair production with W-boson-mediated decays in Chargino vs Neutralino plane [46]

In contrast to simplified models, **pMSSM** captures complex decay chains. The primary goal of the **pMSSM** is to compress the **MSSM**'s more than 100 parameters down to just 19, shown in Table 2.4. To attain this, a variety of well-motivated experimental constraints are applied, especially the following:

- **Sparticles mass unification:** First and second-generation soft **SUSY**-breaking scalar masses are assumed to be the same.

- **No new sources of CP-violation<sup>7</sup>:** By using experimental limits on the electron and muon magnetic moments, it is assumed that the soft **SUSY** breaking parameters in **MSSM** are real [48].
- **Minimal flavour violation:** No flavour-changing neutral currents are considered by diagonalizing the mass matrices for all sfermions and tri-linear coupling. By making this assumption, flavour physics parameters are reduced [49].
- **R-Parity conservation:** R-parity is conserved, which results in all sparticles produced in pairs.
- **LSP be  $\tilde{\chi}_1^0$  :** the **LSP** will be the lightest neutralino.

The Bino, Wino, and Higgsino parameters in **pMSSM** are responsible for the nature of **EWkinos** such that if the mass parameters are well separated, Neutralinos and Charginos are split into:

- Bino-like<sup>8</sup>: singlet with one neutralino with mass parameter  $\approx |M_1|$
- Wino-like<sup>9</sup>: doublet with two oppositely charged charginos and neutralinos with a mass parameter  $\approx |M_2|$
- Higgsino-like<sup>10</sup>: a quartet with two charginos and two neutralinos with a mass parameter  $\approx |\mu|$

On the contrary, **EWkinos** can mix if mass parameters are not separated.

---

<sup>7</sup>Charge Parity Violation

<sup>8</sup>Fraction of Bino models should greater 50 %

<sup>9</sup>Fraction of Wino models should greater 50 %

<sup>10</sup>Fraction of Higgsino models should greater 50 %

| Parameter                                                                                 | Description                              |
|-------------------------------------------------------------------------------------------|------------------------------------------|
| $M_1$                                                                                     | Bino mass parameter                      |
| $M_2$                                                                                     | Wino mass parameter                      |
| $M_3$                                                                                     | Gluino mass parameter                    |
| $\mu$                                                                                     | Higgs mixing parameter                   |
| $M_A$                                                                                     | Pseudoscalar Higgs mass                  |
| $\tan \beta$                                                                              | Ratio of Higgs vacuum expectation values |
| $A_t$                                                                                     | Trilinear top coupling                   |
| $A_b$                                                                                     | Trilinear bottom coupling                |
| $A_\tau$                                                                                  | Trilinear tau lepton coupling            |
| $m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{\ell}}, m_{\tilde{e}_R}$      | First/second generation sfermion masses  |
| $m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{\tau}}, m_{\tilde{\nu}_\tau}$ | Third generation sfermion masses         |

Table 2.4: Overview of the 19D phenomenological Minimal Supersymmetric Standard Model

## 2.6 Summary

This chapter explores the basics of particle physics, starting with the **SM**. The **SM** explains the fundamental particles and their interactions. It also covers the Brout-Englert-Higgs mechanism, which gives particles mass through the Higgs boson. The chapter highlights the limitations and unanswered questions within the **SM**.

Next, the chapter introduces **SUSY** and explains **MSSM** and its practical version, **pMSSM**. It discusses the search for supersymmetric particles at the **LHC**. To impose constraints on both the strong and **EW** sectors of the **pMSSM**, various **ATLAS** Run 2 **SUSY** searches, which were previously analyzed using simplified models, will be revisited in Chapter 7.

# Chapter 3

## The ATLAS experiment at the Large Hadron Collider

### Contents

---

|            |                                                 |           |
|------------|-------------------------------------------------|-----------|
| <b>3.1</b> | <b>The Large Hadron Collider at CERN</b>        | <b>26</b> |
| <b>3.2</b> | <b>ATLAS - A Toroidal LHC Apparatus</b>         | <b>31</b> |
| <b>3.3</b> | <b>The ATLAS Physics Program</b>                | <b>32</b> |
| <b>3.4</b> | <b>Layers of the ATLAS Detector</b>             | <b>34</b> |
| 3.4.1      | The Inner Detector                              | 35        |
| 3.4.2      | Calorimeters                                    | 37        |
| 3.4.3      | Muon Spectrometer                               | 38        |
| 3.4.4      | Triggering                                      | 39        |
| <b>3.5</b> | <b>Physics Objects Reconstruction</b>           | <b>39</b> |
| 3.5.1      | Initial Objects                                 | 40        |
| 3.5.2      | Electrons and Photons                           | 41        |
| 3.5.3      | Muons                                           | 43        |
| 3.5.4      | Jets                                            | 44        |
| 3.5.5      | Missing transverse momentum                     | 48        |
| <b>3.6</b> | <b>Event generation and detector simulation</b> | <b>49</b> |
| <b>3.7</b> | <b>ATLAS Software Releases</b>                  | <b>50</b> |
| <b>3.8</b> | <b>Summary</b>                                  | <b>51</b> |

---

The main bibliographic sources of this chapter are:

- O. S. Brüning et al., “LHC Design Report” [50]
- ATLAS Collaboration, “ATLAS experiment at the CERN large hadron collider” [51]
- P. Weber, “ATLAS calorimetry: trigger, simulation and jet calibration” [52]

In the previous chapter, we studied the fundamental particles and their properties in detail, demonstrating that the **SM** is a successful model in many respects, but it still leaves several important questions unanswered. We also studied one of its proposed extensions **SUSY**. One fact is that scientific theories are only proven correct when matched with experimental data.

Since the last century, numerous particle accelerators have been constructed, with the Tevatron being one of the most powerful proton-antiproton colliders at Fermi National Laboratory (Fermilab) in the USA. The Tevatron achieved a major breakthrough in 1995 by discovering the top quark [53]. After this discovery, the Higgs boson was the only remaining particle in the **SM** to be detected. Experimental searches, particularly at the **Leptonic (LEP)** colliders (such as electron-positron colliders), established a lower limit on the Higgs boson mass of 114.4 GeV at a 95% confidence level [54]. In addition, experiments at the Tevatron and **LEP 2** provided further constraints on the Higgs mass, showing a multi-peaked probability distribution for the Higgs mass. These results indicated a relatively narrow preferred mass range between 115 GeV and 148 GeV with 90% confidence. These research efforts were crucial in guiding the **LHC**’s experiments, ultimately leading to the discovery of the Higgs boson within this predicted range [55].

**LEP** colliders were limited in their maximum energy due to synchrotron radiation losses, particularly at high energies. Although these limitations suggested the need for alternative solutions, the primary reason for seeking higher energy collisions was to investigate the Higgs boson, as its mass was anticipated to exceed the energy capabilities of the **LEP** colliders. This led to the development of Hadronic colliders, such as proton-proton colliders. These colliders offer higher energy capabilities because protons, being heavier particles, experience less synchrotron radiation and can be accelerated to much higher energies. The higher beam intensity and increased collision rates at hadronic colliders also improve the chances of detecting rare events.

These motivations led to the construction of the **LHC**, the largest and most powerful particle accelerator to date. Subsequently, these collisions are analyzed and reconstructed through various experiments, such as **ATLAS**. The main objective of the **LHC** experiment now is to search beyond the **SM**. The analysis performed in this dissertation has been done using data collected by **ATLAS**, so the main focus of this chapter is to study this experiment.



First, I will provide a brief explanation of **LHC**, including its operating schedule. Then, I will discuss the **ATLAS** detector and its essential components one by one from section 3.2 onwards.

### 3.1 The Large Hadron Collider at CERN

**LHC** was built at **CERN**, located near Geneva and stretching across the France-Switzerland border. It is an international high-energy physics collaboration with 24 member states and over 20,000 scientists worldwide. Over 600 institutions around the world use **CERN** facilities. **LHC** is located in a 100-meter-deep tunnel with a circumference of 26.7 km. During its running years, the detectors located on the **LHC** generate vast amounts of data, around an exabyte of data per year for analysis. The **LHC**'s aerial view can be seen in Figure 3.1.

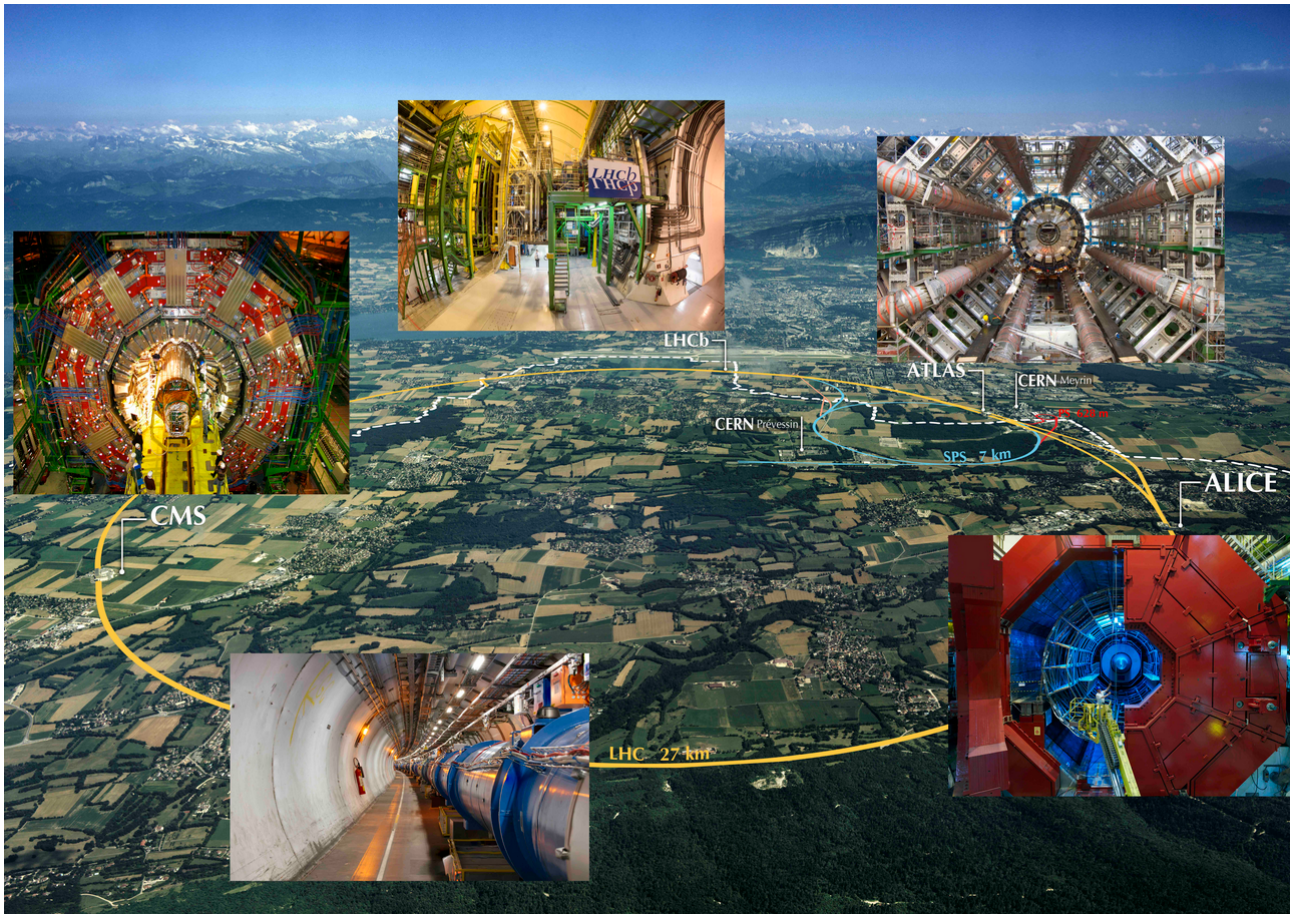


Figure 3.1: Aerial view of LHC at CERN [56]

The first exploitation period of **LHC** occurred from 2010-2013 at the energy of 3.5 TeV to 4 TeV with the center of mass energy of 7 to 8 TeV. After this period, the **LHC** went through maintenance and minor upgrades over two years. It resumed operations in 2015 at 6.5 TeV energy with 13 TeV center of mass energy; Figure 3.2 shows the complete run schedule of **LHC**, taking into account both its upgrades and operational period.

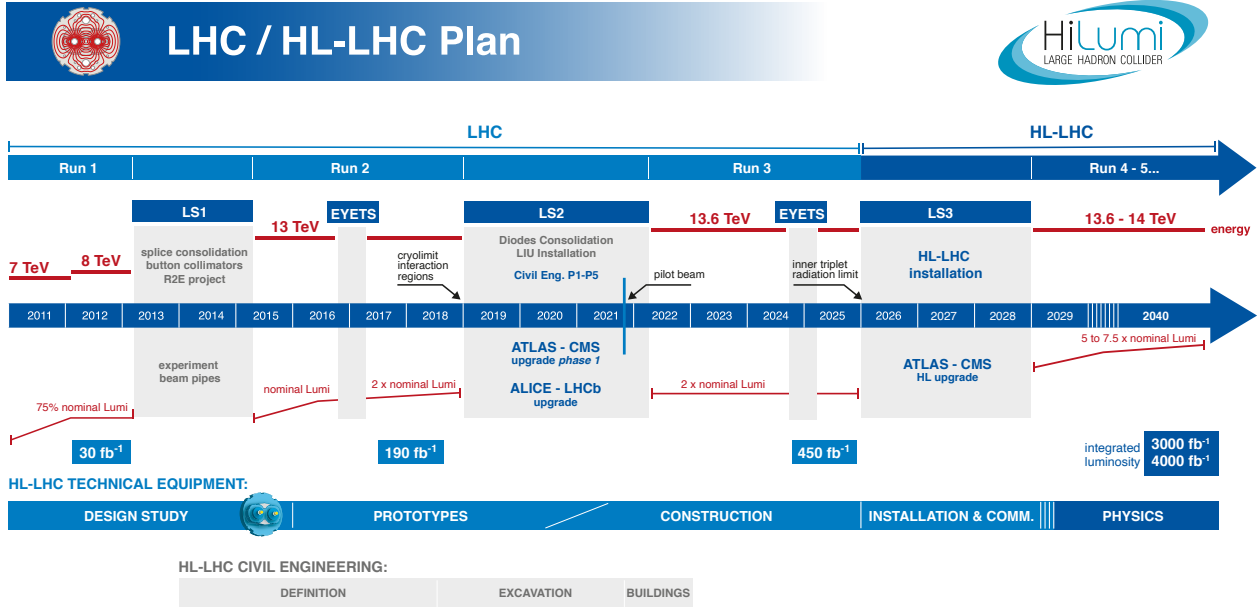


Figure 3.2: LHC and HL-LHC Schedule as of 5 Dec 2014 [57]

## Design of LHC

At **LHC**, the particles circulate in two distinct beams in opposite directions, and interaction occurs at four different points. The design of the **LHC** incorporates more than 2500 magnets, including 1232 superconducting dipoles used to bend the beams and maintain their circular trajectory.

Magnets operate at a temperature of 1.9 K. Magnets produce a magnetic field of 8.3 T. Additionally, 392 superconducting quadrupole magnets are used to focus the beam. In the design parameters of the **LHC**, there are 2,808 bunches, each containing approximately  $1.05 \times 10^{11}$  protons, with a bunch spacing of 25 ns. However, these parameters can vary depending on the operational conditions in a given year. For example, during the 2017 run, the **LHC** operated with 2,556 bunches per ring, each containing  $1.15 \times 10^{11}$  protons at a beam energy of 6.5 TeV. This configuration resulted in a stored energy of around 300 MJ per beam. An electric field is initially applied to ionise hydrogen gas, producing protons. Further, the protons in the **LHC** pass through a chain of accelerators. Initially, it starts from LINAC2<sup>1</sup>, which boosts the protons to the energy of 50 MeV. After that, it is injected into a **Proton Synchrotron Booster (PSB)**, which is boosted up to the energy of 1.4 GeV and then further moved to **Proton Synchrotron (PS)**, which accelerates them to the energy of 2.6 GeV. Another **Super**

<sup>1</sup>After 2018, LINAC4 replaced LINAC2, providing increased energy of 160 MeV to the protons.

## The CERN accelerator complex *Complexe des accélérateurs du CERN*

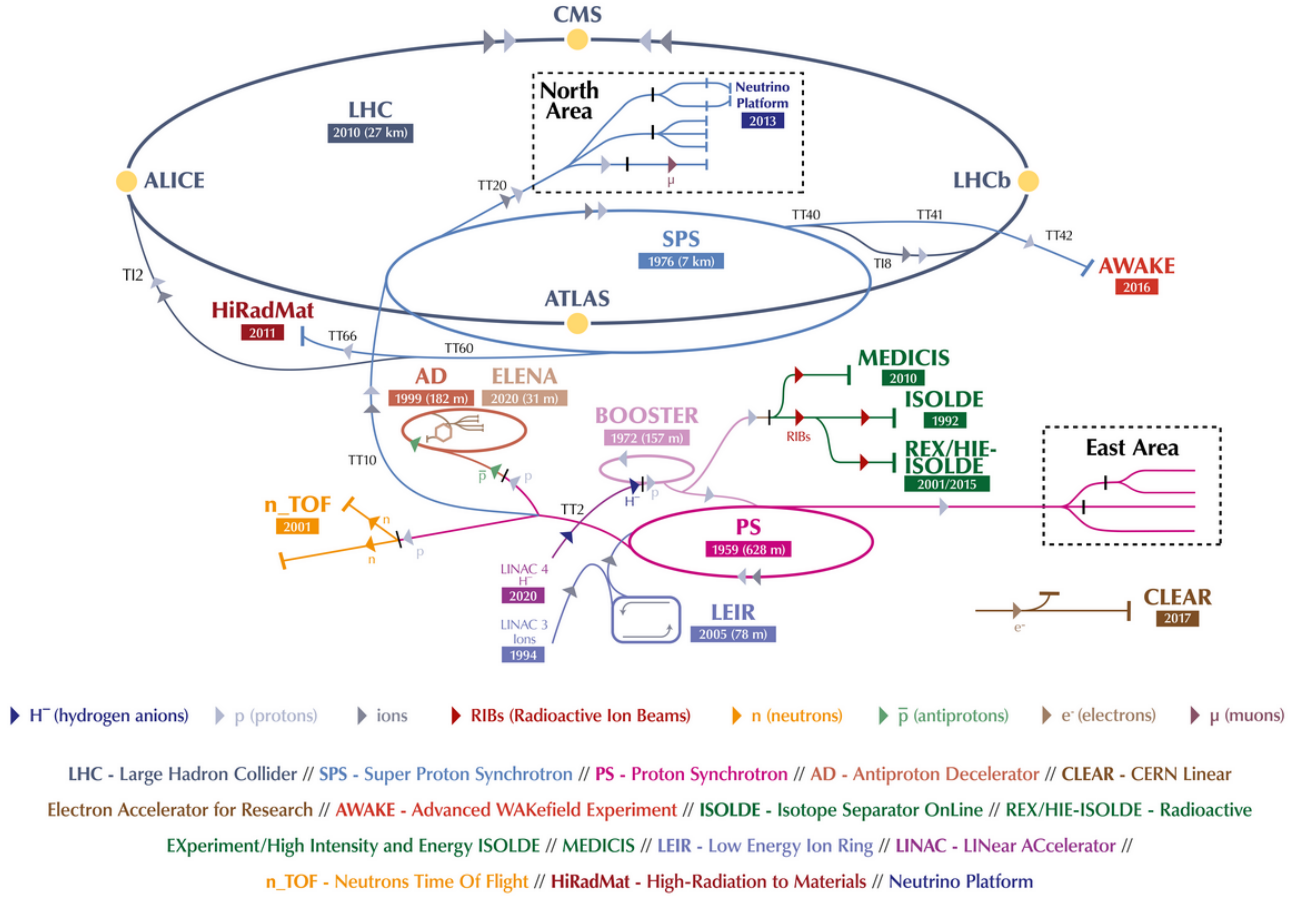


Figure 3.3: Overview of complex experimental accelerators at CERN [58]

**Proton Synchrotron (SPS)** is used, which speeds up the protons at the energy of 450 GeV. At this stage, the protons are injected into the **LHC** ring, where they are first accelerated from 450 GeV to energies between 3.5 TeV and 6.8 TeV, allowing interactions to occur at four specific points within the ring. The entire chain of accelerators, along with the rest of the complex structure of the **LHC**, is depicted in Figure 3.3.

### Major experiments at the LHC

The main points of interactions at **LHC**, as shown in Figure 3.1, are listed below:

- **ATLAS** “A Toroidal LHC ApparatuS” is a general-purpose detector of **LHC** that will be discussed thoroughly in the later sections [51].
- **CMS** “Compact Muon Solenoid” is also a general-purpose detector like **ATLAS** but with different designs and characteristics [59]. The one key difference is that the **ATLAS** uses a large toroidal magnet system for precise tracking and calorimetry, while **CMS** employs a more compact, high-field solenoid for superior momentum resolution.

- **ALICE** “A Large Ion Collider Experiment” examines the particles from lead-ion collisions. Its main purpose is to study the **Quark Gluon Plasma (QGP)**. **QGP** is a state thought to have existed right after the Big Bang [60].
- **LHCb** “Large Hadron Collider beauty” is a particle physics experiment designed to conduct precise measurements of heavy flavor particles, particularly those containing beauty (b) and charm (c) quarks, in order to explore fundamental questions in particle physics, including the nature of CP violation and potential new physics phenomena **BSM** [61].

## How are different processes observed at the LHC?

In simple terms, different processes at the **LHC** produce various events. Many events need to be produced to detect rare processes, such as those predicted by **SUSY**. The total number of collision events produced by the **LHC** is provided by

$$N = L \times \sigma \times \epsilon \quad (3.1)$$

where  $\epsilon$  is the efficiency of the detector<sup>2</sup>,  $\sigma$  is the cross section<sup>3</sup> of the process under study, and  $L$  is the integrated luminosity given as

$$L = \int \mathcal{L}_{inst.}(t) dt \quad (3.2)$$

where  $\mathcal{L}_{inst.}$  is the instantaneous luminosity reaches to  $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  [62]. Most of the analysis work in this thesis uses data from the period 2015-2018, often referred to as Run 2, corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$ . The delivered and observed integrated luminosity for **ATLAS** Run 2 data is displayed in Figure 3.4a. Additionally, I have worked with early **ATLAS** Run 3 data, which corresponds to a luminosity of  $3.391 \text{ fb}^{-1}$ . The integrated luminosity for Run 3 data is shown in Figure 3.5a. Another remark regarding luminosity is that as we increase instantaneous luminosity per bunch crossing, we may face significant pile-up (multiple proton-proton interactions per bunch crossing given in Figures 3.4b and 3.5b) issues. This can complicate our physics analyses, particularly regarding handling low-momentum particles. Pile-up is very important for future upgrades, such as the **High-Luminosity Large Hadron Collider (HL-LHC)**, which aims to deliver exceptionally high luminosity. Several strategies

---

<sup>2</sup>Efficiency of the detector: Percentage of events that are truly observed and identified.

<sup>3</sup>Probability that a specific interaction will take place.



are used to reduce pile-up in physics analyses and properly address this issue in future upgrades.

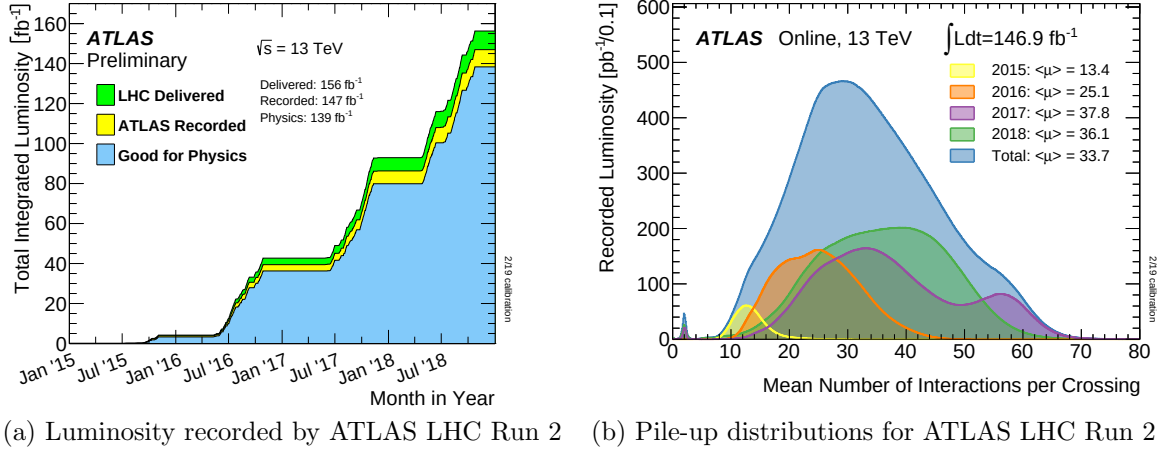


Figure 3.4: (a) illustrates the total integrated luminosity provided to the LHC, depicted in green, with ATLAS-recorded luminosity shown in yellow, and the portion deemed suitable for physics analyses displayed in blue, covering full Run 2. (b) presents the luminosity-weighted distribution of the average number of interactions per bunch crossing throughout Run 2. Both figures are sourced from Ref. [63].

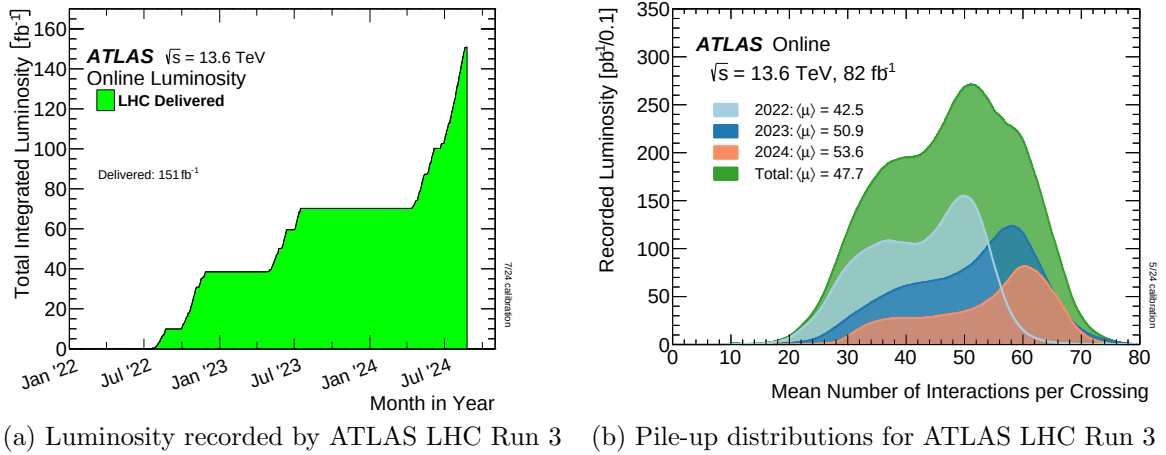


Figure 3.5: (a) illustrates the total integrated luminosity delivered by the LHC for the first two years and ongoing third year of Run 3 (b) presents the luminosity-weighted distribution of the average number of interactions per bunch crossing for the first two years and ongoing third year of Run 3. Both figures are sourced from Ref. [64].

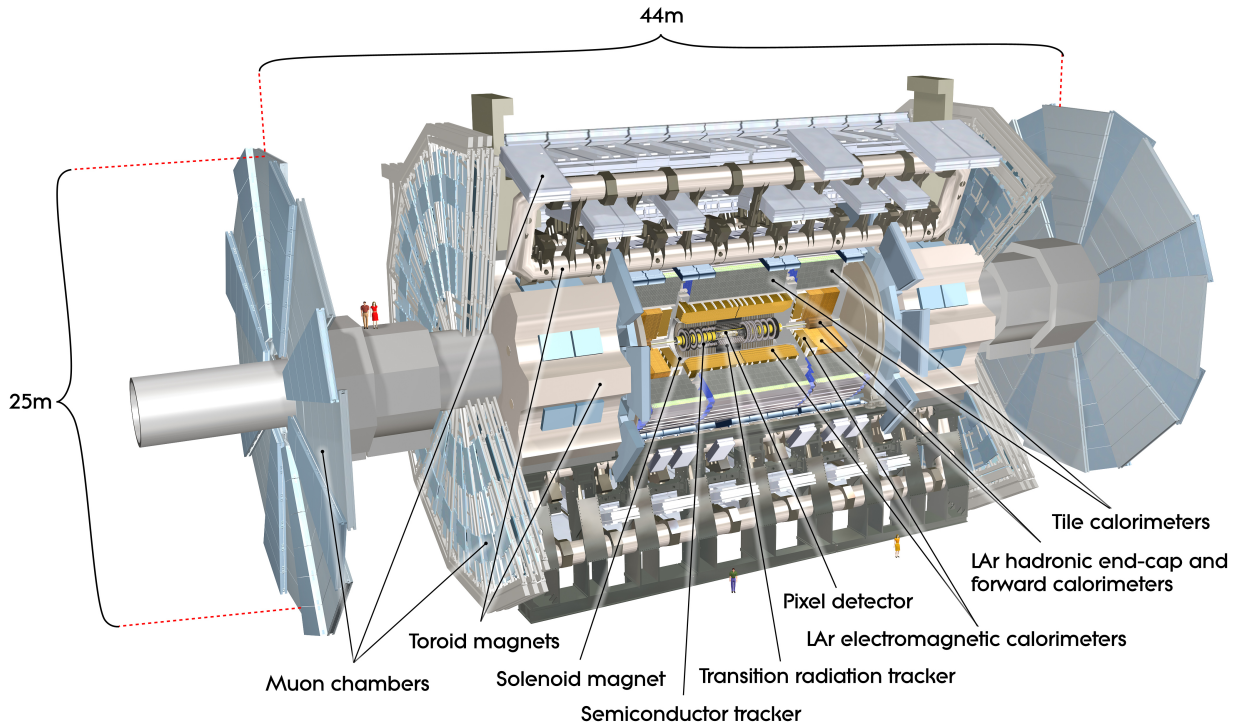


Figure 3.6: Computer generated picture of ATLAS detector showing its different parts of ATLAS detector taken from reference [65].

## 3.2 ATLAS - A Toroidal LHC Apparatus

The **ATLAS** is one of the detectors at the **LHC**. Its flexible design enables it to identify a wide variety of particles. One of its primary goals was to discover the Higgs boson, which was achieved in 2012. However, in addition to detecting the Higgs boson, **ATLAS** was also built to carry out precise measurements of other **SM** particles, like the  $W$  boson and the top quark.

From the beginning, **BSM** searches were another key focus of **ATLAS**. For instance, its **Electromagnetic Calorimeter (ECAL)** was designed to capture electron showers with energies up to the TeV range. This capability is crucial for detecting particles such as  $Z'$  boson candidates [66, 67]. The outstanding versatility of **ATLAS** makes it essential not only for **SM** measurements but also for the continuing search for new physics **BSM**, including **SUSY** and other exotic particles. A bit more detail on the **ATLAS** physics program can be found in section 3.3.

**ATLAS** has not yet directly detected neutrinos among the **SM** particles because neutrinos leave no trace in the detector when they pass through it. It's possible that supersymmetric particles could behave similarly, escaping the detector without leaving a noticeable signature; if they are not weakly interacting, then they will interact with the detector. The three primary

sub-detectors of the **ATLAS** detector are the **Inner Detector (ID)**, calorimetry, and **Muon Spectrometer (MS)**. The general overview of **ATLAS** detector is depicted in figure 3.6.

## Geometry of ATLAS

A cylindrical coordinate system involves three coordinates  $(r, \theta, z)$  where  $r$  is the radial distance from the point of origin in the  $xy$ -plane,  $\theta$  represents the azimuthal angle around the  $z$ -axis, and  $z$  represents the height along the axis of symmetry. **ATLAS** used a cylindrical coordinate system where the  $x$ -axis points to the center of the **LHC** ring, the  $y$ -axis points direction upwards to the surface, and the  $z$ -axis directs to the beam pipe referred to as the collision axis. The azimuthal angle  $\phi$  is measured around the  $z$ -axis in the  $xy$ -plane, representing the particle's angular position relative to the beamline. Additionally, the motion of particles along the beam direction is often described using rapidity, which is defined as:

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \quad (3.3)$$

where  $E$  and  $p_z$  are the energy and momentum along the  $z$ -axis of an object, respectively. In experimental particle physics, a similar quantity that is frequently used is pseudorapidity. It is defined in terms of polar angle as:

$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \quad (3.4)$$

The direction of the momentum of an object in **ATLAS** is defined in terms of  $\eta$  and  $\phi$  where the separation between them can be measured by a quantity named  $\Delta R$  defined as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \quad (3.5)$$

where  $\Delta\eta$  and  $\Delta\phi$  are the differences between the values of  $\eta$  and  $\phi$  respectively.

## 3.3 The ATLAS Physics Program

---

The **ATLAS** detector is crucial for expanding our understanding of fundamental physics. Its broad physics program includes precise measurements within the **SM** and new physics searches for **BSM** phenomena. This program includes key studies such as the detailed investigation of the Higgs boson, alongside extensive searches for potential **BSM** particles, including **DM** and **SUSY** candidates.

One of the main objectives of the **ATLAS** experiment is to test predictions from the **SM** [68]. By making precise measurements of **SM** processes, **ATLAS** has gathered significant data on particle masses, interactions, and decay rates, strengthening the theory’s validity [69]. A key focus of **SM** research is the detailed study of the Higgs boson, along with the W and Z bosons, and the top quark [70–73].

The discovery of the Higgs boson in 2012 was a key moment for particle physics [74]. Both the **ATLAS** and **CMS** detectors played a crucial role. Today, the study of the Higgs boson remains central to the **ATLAS** Physics Programme, with ongoing research aimed at refining our understanding of its interactions with other particles [75]. Future experiments at the **LHC** may reveal rare Higgs decays, with the goal of determining whether the rates of such decays align with **SM** predictions or indicate new physics **BSM**.

In addition to **SM** validation, **ATLAS** is also deeply involved in the search for **BSM** phenomena. The **SM**, despite its successes, leaves many unanswered questions. The search for new particles predicted by **BSM** theories, such as heavier Higgs and gauge bosons and vector-like quarks, could offer new understandings of physics **BSM**. One of the prominent areas is the search for **SUSY** particles in several scenarios [76], which could answer many unanswered questions by **SM**.

**ATLAS** is also actively searching for **DM** particles, which are hypothesized to make up around 85% of the universe’s matter. Though **DM** does not interact electromagnetically and cannot be detected directly, **ATLAS** looks for its presence through missing transverse energy events [77].

So far, no direct evidence of **DM** or **SUSY** particles has been found, but the constraints provided by **ATLAS** data are narrowing down the range of possibilities [76]. The higher energy levels and luminosity in future **LHC** runs offer hope for breakthroughs in these areas.



### 3.4 Layers of the ATLAS Detector

---

The **ATLAS** detector is like an onion with different layers called sub-detectors, as shown in figure 3.7. The **ID**, which detects charged particles, is the first layer of the detector. Additional calorimeters include **Hadronic Calorimeter (HCAL)**, which measures the energies of charged and neutral hadrons like pions, and **ECAL**, which measures the energies of electrons and photons by absorbing them. The outermost layer, called the **MS**, measures muon momenta independently. Details of each of these components are covered separately in a later section.

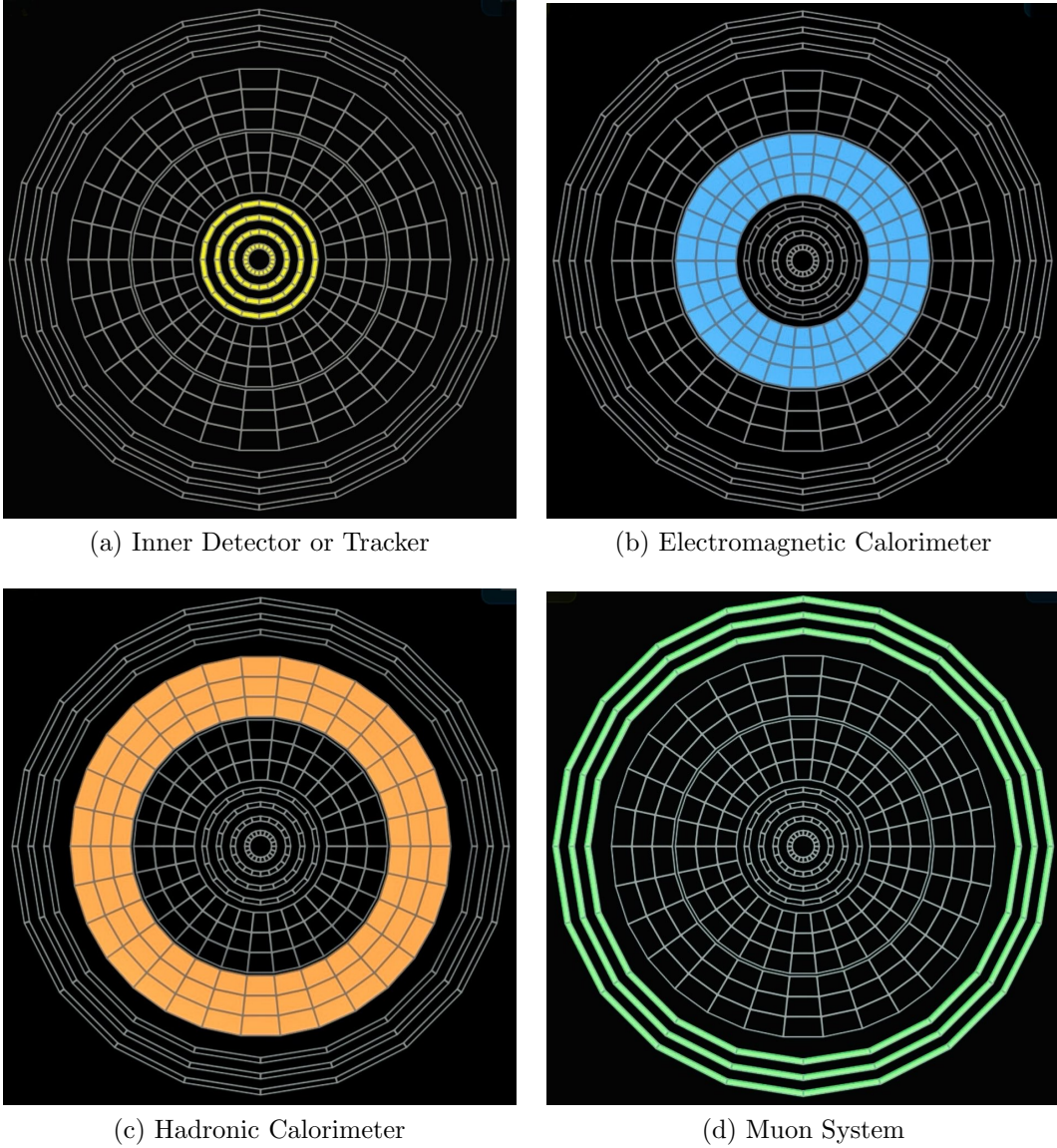


Figure 3.7: General view of different components of ATLAS detector by layers.

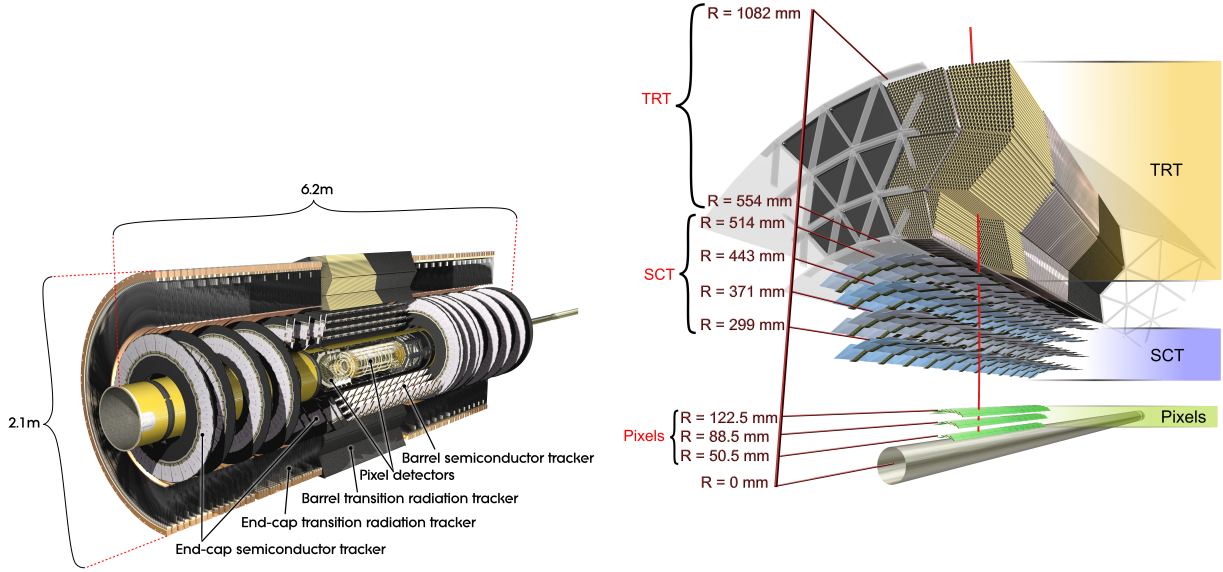


Figure 3.8: Computer generated image of ATLAS Inner Detector taken from reference [78]

### 3.4.1 The Inner Detector

The first layer of the **ATLAS** detector is referred to as the **ID** illustrated in figure 3.8, whose primary purpose is to reconstruct the trajectory of particles produced in proton-proton collisions. It aims to detect both primary and secondary vertices. Additionally, it measures the curved paths of charged particles, facilitated by its embedding in a 2 Tesla magnetic field generated by a superconducting solenoid. This curvature enables the measurement of the particle's charge and transverse momentum. Overall, the **ID** provides information on tracks and momentum for  $|\eta| < 2.5$  and  $P_T > 0.5$  GeV. The **ID** consists of three sub-detectors: a Silicon pixel detector, a strip-based semi-conductor tracker, and a transition radiation tracker.

The **pixel detector** has been positioned very close to the interaction point, only a few centimeters away, allowing it to detect short-lived particles effectively. It comprises over 1700 modules, each consisting of approximately 47,000 pixels. Constructed in three concentric barrel layers, it includes two endcaps containing three disks. The **Insertable B-Layer (IBL)** was added after **LHC** Run 1 to enhance track resolution and flavour tagging by incorporating extra hits near the interaction point.

The **Semiconductor Tracker (SCT)** detector consists of around 6 million silicon microstrips, arranged in 4,088 modules that are organised into four concentric layers, with two endcaps, each containing nine disks. These microstrips are an integral part of the **SCT** and play a key role in tracking charged particles. The **SCT** provides a spatial resolution of approximately  $17 \mu\text{m}$  in the plane perpendicular to the beamline and about  $580 \mu\text{m}$  along the beam direction.

Although this resolution is less precise than that of the pixel detector, which offers around  $10\text{ }\mu\text{m}$  and  $115\text{ }\mu\text{m}$  in these respective directions, the **SCT**'s larger coverage area makes it essential for tracking particles across a wider region of the detector [79]. The **SCT**'s primary function is to distinguish between the many-particle trajectories produced in the dense environment of **LHC** collisions. With numerous tracks generated in each event, the detector's high precision ensures that these tracks can be reconstructed without ambiguity or overlap.

The **ID** is surrounded by the **Transition Radiation Tracker (TRT)** [80]. The **TRT** consists of several hundred thousand drift tubes (or straws) filled with a gas mixture. When a particle passes near these gas-filled straws, it ionises the gas, producing a detectable signal. This component of the **ATLAS** detector is particularly effective at identifying electrons because it detects transition radiation. This type of radiation occurs when high-energy charged particles, especially electrons, pass through the boundaries of materials with different properties. Due to their higher energy and speed, electrons emit more transition radiation than other particles like pions. This difference helps the **TRT** distinguish electrons from hadrons [81]. The **TRT** covers the pseudorapidity range of  $|\eta| < 2.0$ .

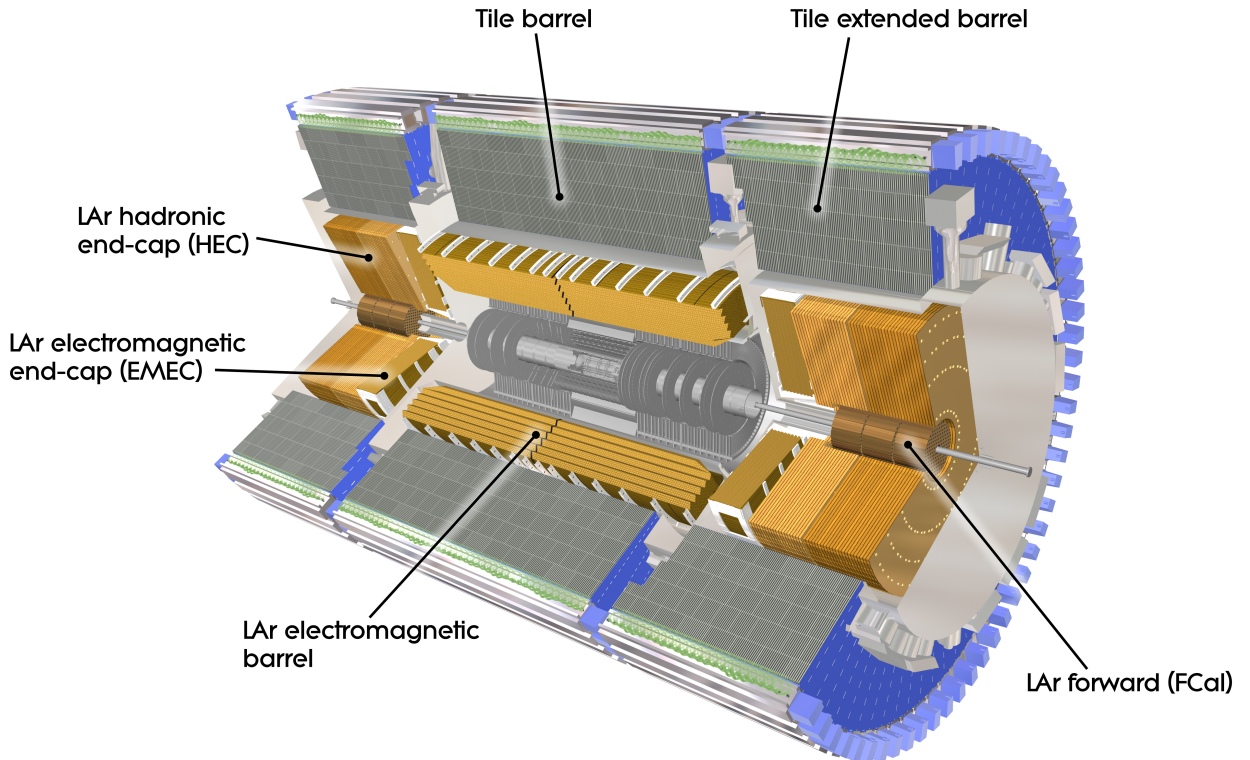


Figure 3.9: Computer generated picture of ATLAS Calorimeters [82].

### 3.4.2 Calorimeters

Calorimeters shown in figure 3.9 placed around the **ID** are used to measure the energy of particles by absorbing them and then converting them into a measurable signal. The **ECAL** uses liquid argon to measure energy through ionisation, while the **HCAL** contains with **ECAL** measures energy through the scintillation light. When particles interact with the material inside the calorimeter, they produce showers of secondary particles. The energy deposited in the calorimeter is proportional to the intensity and size of these showers.

The **ATLAS** calorimeters detect both charged and neutral particles. There are two calorimeters: one is **ECAL**, capable of measuring the energy of electrons and photons, with a coverage of  $|\eta| < 3.2$ , while the other is **HCAL** contains with **ECAL**, can measure the energy of hadrons, with a coverage of  $|\eta| < 4.9$ . The **ATLAS** detector uses sampling calorimeters made up of alternating layers of active material and absorbing material. The purpose of this design is that when a particle enters the calorimeter, it first interacts with the absorbing layers, typically made of high-density materials, where the initial particle generates a shower of secondary particles. These secondary particles then travel through the absorbing material and eventually reach the active medium, where they deposit their remaining energy, causing ionisation or scintillation, which can be measured. The purpose of this design is that when a particle enters the calorimeter, it first interacts with the absorbing layers, typically made of high-density materials, where the initial particle generates a shower of secondary particles. These secondary particles then travel through the absorbing material and eventually reach the active medium, where they deposit their remaining energy, causing ionisation or scintillation, which can be measured.

**ECAL** is one of the main components of **ATLAS** detector; as its name suggests, it is designed to detect any particle interacting through **EM** interaction. There are lead absorbers in the barrel region of the **ECAL**, while the gaps between absorbers are filled with **Liquid Argon (LAr)**. When particles strike the lead absorbers, they produce showers of low-energy particles, ionising the **LAr**, generating a measurable electric current by capacitive coupling. Summing this detectable current can eventually give the energy of the original particle that hit the detector.

**HCAL** is positioned surrounding the **ECAL** within the **ATLAS** detector, constituting its heaviest component. Its primary objective is to detect particles that interact via strong interactions. **HCAL** comprises three main components: the **Tile Calorimeters**, which cover the outer region, utilising steel absorbers and 420,000 plastic scintillating tiles arranged in three layers formed by many modules. When charged particles interact, they produce light in the



scintillators, which is collected via wavelength-shifting optical fibers, and the Photomultiplier tubes further measure these signals.

The other two components are the **Hadronic Endcap (HEC)** and **Forward Calorimeters (FCAL)**, providing additional coverage up to  $|\eta| < 4.5$ .

### 3.4.3 Muon Spectrometer

Muons are the particles that pass through the **ECAL** and **HCAL**. Still, they can be detected in the **ATLAS** detector using **MS**, as shown in figure 3.10. This detector is crucial to measure muons' track, momentum, and energy if they are produced after collisions. The point of origin (vertex) of muons can be detected by the **ID**, while the **MS** primarily determines their momentum and trajectory. Numerous tracking chambers and a strong magnetic system are combined to construct the muons in the spectrometer by utilising multiple detection technologies.

Speaking of the **magnetic system**, it is essentially provided by three toroidal magnet systems, with one located in the barrel region ( $-1.1 < \eta < 1.1$ ) and two in the end cap region ( $1.1 < |\eta| < 2.7$ ). The barrel toroid is constructed from 8 superconducting coils, generating a magnetic field reaching 4 teslas.

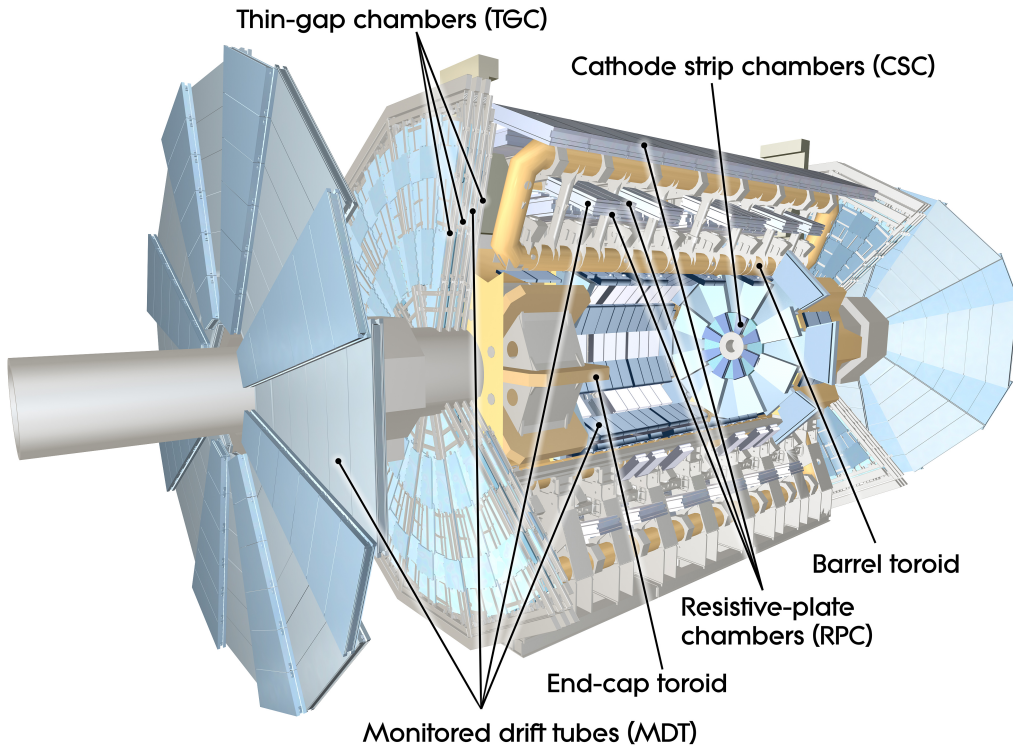


Figure 3.10: Computer generated picture of ATLAS Calorimeters Muon Spectrometer [83].

Precise measurements of muon trajectories are achieved through **Monitored drift tubes (MDTs)** and **Cathode strip chambers (CSCs)** covering more area of the MS. MDTs

operate by detecting ionisation produced by charged particles moving through a tube filled with a mixture of Argon and carbon dioxide gases, providing total coverage in the range  $-2.7 < \eta < 2.7$ . **CSCs** are fast-timing detectors used in the forward region of the spectrometer. The timing resolution of **MDTs** is 700 ns, while **CSCs** offer an improved timing resolution of 40 ns. Overall, muon momentum is measured very precisely but with a slow response time, necessitating faster measurements for further triggering<sup>4</sup>.

Faster measurements are provided by **Resistive plate chambers (RPCs)**, which are essentially gas-filled parallel plates. Muons passing through ionise the gas, creating avalanches that are detected. **Thin gap chambers (TGCs)** extend the spectrometer coverage consisting of multi-wire proportional chambers. **RPCs** have a response time of 1.5 ns, while **TGCs** have a response time of 4 ns, making them perfect for triggering purposes.

### 3.4.4 Triggering

The **LHC** generates proton bunch collisions at a frequency of 40 MHz. To save these events, a lot of data must be stored. To handle this, a two-level triggering system is used to identify and save the most exciting events. Events with high- $p_T$  objects (electrons, muons, photons, taus, or jets) or high-missing transverse momentum are thought to be interesting.

The level 1 (L1) hardware-based trigger initially lowers the event rate to 100 kHz. It makes a rough but fast ( $< 2.5 \mu s$ ) initial trigger decision using low-level detector data from the calorimeters and **MS**. The L1 trigger's electronics are kept in the **ATLAS** cavern to lower the trigger decision's delays. Subsequently, the event rate is decreased to 1 kHz by the software-based **High-level trigger (HLT)**. The **HLT** can quickly reconstruct signals from a more extensive range of detector subsystems for the triggering decision because it has enough time (about 300 ms per event).

## 3.5 Physics Objects Reconstruction

---

The previous sections emphasised how detectors respond to different event components, whether in the form of hits or energy depositions. However, we are primarily interested in the kinematics of particles, such as their momentum, as well as identifying and reconstructing physics objects like jets, electrons, and muons. This requires object reconstruction, which refers to extracting information about particles and other physical entities from raw data.

---

<sup>4</sup>Rapidly identifies and selects interesting collision events

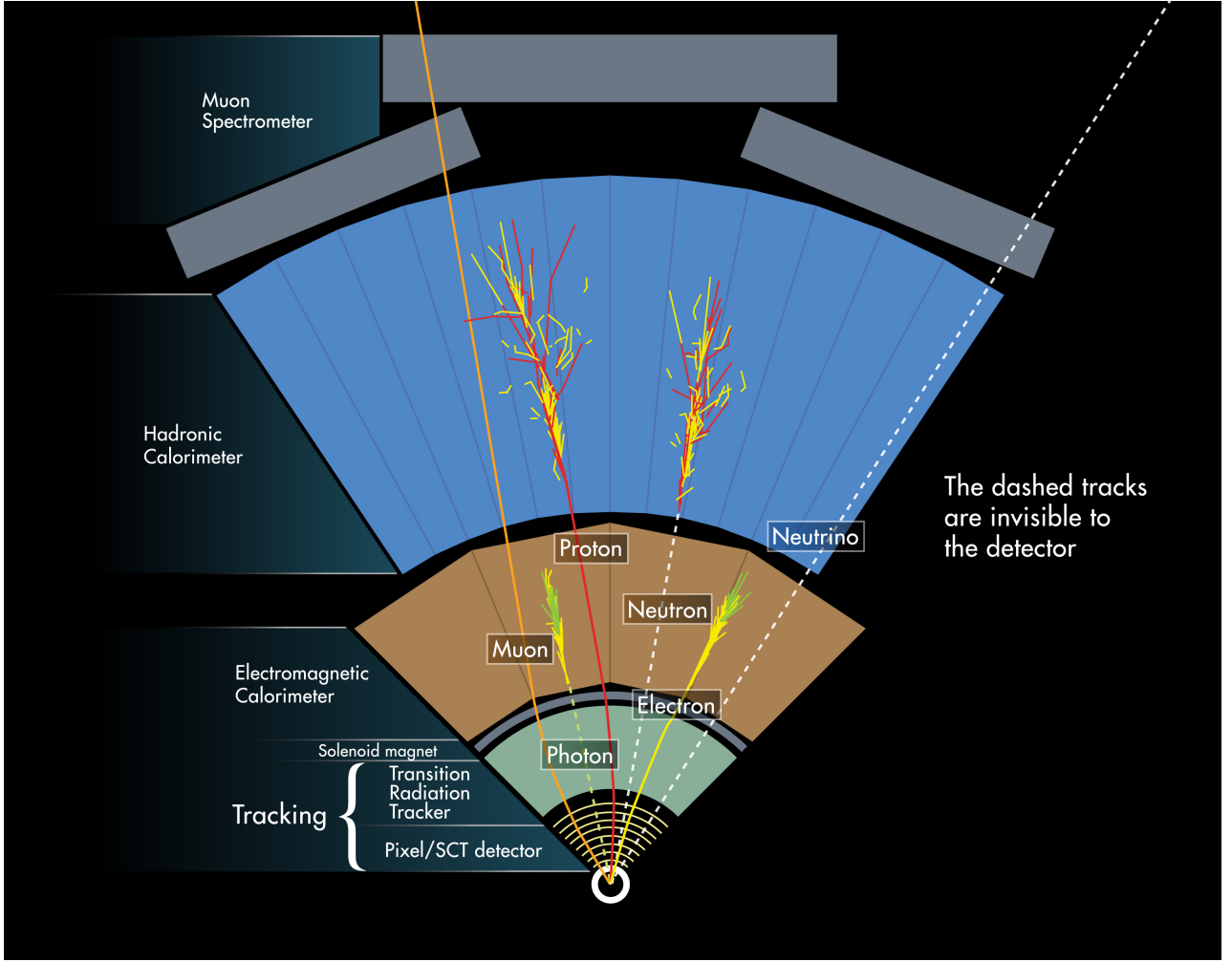


Figure 3.11: Computer generated picture of particle paths in the ATLAS detector[84].

This section will examine the procedures for reconstructing critical objects in the **ATLAS** detector, including electrons, photons, muons, jets, and missing transverse energy. Figure 3.11 provides an overview of the reconstruction of different particles.

### 3.5.1 Initial Objects

High-level objects, such as electrons, are reconstructed from low-level objects, like vertices and tracks, coming together. Raw hits produced in different sections of the **ATLAS** detector are used to form tracks, while vertices refer to the origin of these tracks.

Each high-level object is reconstructed independently in the **ATLAS** detector. This can sometimes lead to a single track contributing to the reconstruction of different objects, resulting in potential double counting. To reduce this, overlap removal procedures are applied. Particular selection criteria are used to minimise the inclusion of fake tracks, considering parameters such as the number of hits (space points), number of holes (locations where hits are expected but not found), and number of outliers (space points that reduce the quality of the fit). The impact

parameter<sup>5</sup> and  $z_0$ <sup>6</sup> of each reconstructed track are determined by fitting the track's trajectory to the primary interaction point. This trajectory fitting process is refined using algorithms such as the Kalman Filter, which optimally reconstructs helical paths within the magnetic field by iteratively updating track parameters as more data from the **ID** is incorporated. This process differs from the fit used to determine the track's momentum, which is based on the curvature of the track as it moves through the magnetic field [85]. The primary vertex, often called the first vertex of any event, holds significant importance. It is characterised by having the highest sum of  $P_T^2$  from all the associated tracks with  $P_T > 500$  MeV. During the vertex reconstruction process, multiple vertices are produced. One of these vertices is selected as the primary vertex. Once the primary vertex is selected, the search for additional vertices continues. These additional vertices, known as secondary vertices, often originate from pileup interactions or other unrelated collisions. The reconstruction process uses the remaining tracks to identify these vertices until no tracks are left. However, this process becomes challenging in high-luminosity environments due to the complexity of distinguishing between overlapping events.

### 3.5.2 Electrons and Photons

The **ATLAS** detector mainly reconstructs electrons in the central region initiated from clusters of energy in the calorimeter, which are then associated with tracks in the **ID**. Essentially, the **ECAL** constructs clusters by dividing itself into a grid of towers and then measuring the energy in each tower. A cluster is formed when a group of adjacent towers records significant energy deposits, indicating the passage of an electron or photon. This process effectively sums the energy contributions from all calorimeter layers to reconstruct the total energy of the particle. Reconstructing electrons and then identifying them as true or prompt electrons (produced directly from the primary interaction) is a challenging task. Identification involves discriminating between true and fake or non-prompt electron candidates, which may arise from background noise or other sources, such as photon conversions or misreconstructed particles.

In the **ATLAS** detector, the reconstruction of an electron begins with the energy deposit (cluster) in the **ECAL**, which is then associated with the reconstructed tracks of charged particles in the **ID**. To rebuild an **EM** cluster, seed clusters are first identified using a sliding windows algorithm, which scans the calorimeter in fixed-sized regions to find local maxima of energy deposits. These maxima are the starting point for cluster formation [87]. Once the initial

---

<sup>5</sup>The distance measured in the x,y plane between the end of closest approach and the z-axis

<sup>6</sup>the z-coordinate at the z-axis's closest approach point



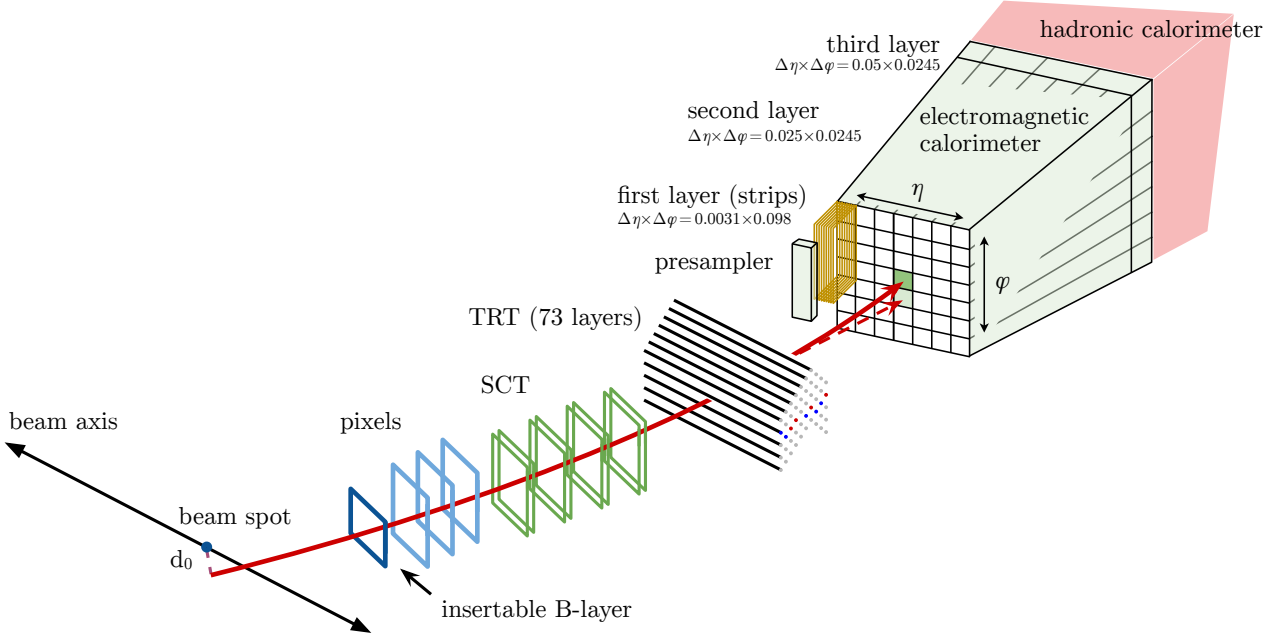


Figure 3.12: A diagram depicting the electron’s journey through the ECAL and different sections of the ID within the ATLAS detector. The red line represents a hypothetical electron path, beginning in the tracking system before passing into the ECAL. The dashed red line illustrates the path of a photon generated from the electron’s interaction with the material in the tracking system [86].

seed cluster is identified, the next step involves creating a supercluster by combining additional energy deposits from nearby cells. This allows for a more comprehensive collection of the electron’s energy. Following this, the track associated with the cluster undergoes a **Gaussian-Sum Filter (GSF)** track refit [88], which refines the trajectory of the electron, accounting for multiple scattering and energy loss in the detector material. An electron is successfully reconstructed when at least one track is matched to the supercluster [87]. The efficiency of this matching process and the subsequent track quality cuts is referred to as electron reconstruction efficiency [89], explained in detail in chapter 4. An illustration of the path of an electron through the **ATLAS** detector is shown in Figure 3.12.

Once an electron is reconstructed, the next task is determining whether it is a prompt or a non-prompt electron. In the **ATLAS** detector, this distinction is made using multivariate analysis techniques, including likelihood-based methods. In this process, all relevant information (such as track and calorimeter cluster properties) from the reconstruction step is recalled and compared against established patterns for both prompt and non-prompt electrons. Based on these comparisons, a likelihood ratio is calculated, representing the probability that the electron is either a prompt (if it originates directly from the primary interaction) or non-prompt. The likelihood-based method combines these variables into a single discriminant value, which serves as the basis for the final classification. The effectiveness of this classification is measured by

the electron identification efficiency, which reflects how accurately the algorithm distinguishes between prompt and non-prompt electrons. Different working points are applied to optimise the balance between selection efficiency and background rejection, with typical identification efficiencies ranging from 80% to 93%, depending on the criteria used. Further details about electron identification can be found in Ref. [89].

Parallel reconstructions of photons and electrons use the same set of detector information. This process distinguishes between converted<sup>7</sup> and unconverted photons<sup>8</sup>. Converted photons are typically associated with one or two reconstructed tracks, while unconverted photons have no associated tracks. Additionally, photons and electrons also have different **EM** shower shapes. Photons have narrower showers than electrons. Photon candidates must be separated from other nearby particles within a cone of  $\Delta R = 0.4$  surrounding the photon, and this requires extra energy such that  $E_T^{iso} < 4 \text{ GeV}$ . Three methods based on data are used to obtain the photon identification efficiency. The first method uses a pure photon sample from radiative  $Z \rightarrow \ell\gamma$  decays, where  $\ell$  can be a muon or electron. The second method uses electrons from  $Z$  decays and converts their discriminating variables to photons. The third method uses a matrix that utilizes track isolation. Further details about photon identification can be found in the Ref. [89].

### 3.5.3 Muons

In the **ATLAS** experiment, muons ( $\mu$ ) produced at the collision point ideally travel through several detector systems: the **ID**, calorimeters, and the **MS**. Due to various constraints, muons might not leave signals in all these systems. To improve the muons reconstruction efficiency, **ATLAS** employs five strategies [90]:

- **Combined (CB) Muons:** If  $|\eta| < 2.5$ , **ID** and **MS** tracks are combined. For  $|\eta| > 2.5$ , hits in the Pixel and **SCT** detectors are used in place of the full **ID**. This method requires complete tracks from both the **ID** and **MS**, resulting in the most accurate muon momentum measurement.
- **Inside-out (IO) CB Muons:** For low  $p_T$  muons or those passing through **MS** gaps (areas where the muon detector has limited coverage and might not record hits), if three hits in **MS** form a rough track, they are considered **IO** muons, even without a complete **ID** track. This strategy allows for the reconstruction of muons where more stringent tracking requirements cannot be met, but at the cost of reduced momentum resolution

---

<sup>7</sup>Converted Photons: Photons that transformed into a pair of electrons and positrons

<sup>8</sup>Unconverted Photons: Photons that do not convert into a pair of electrons and positrons

compared to **CB** and **Muon-spectrometer Extrapolated (ME)** muons.

- **ME Muons:** For muons with large  $|\eta|$  values, where **MS** tracks are available but **ID** tracks are incomplete, the **MS** track is extrapolated inward to check for vertex matching. Unlike **CB** muons, **ME** muons rely entirely on the **MS** for momentum measurements, resulting in lower resolution compared to combined muons but higher than **IO** muons.
- **Segment-tagged (ST) Muons:** When there is a complete **ID** track and at least one short segment in **MS** <sup>9</sup>. The parameters from the **ID** track are then used directly for reconstruction.
- **Calorimeter-tagged (CT) Muons:** For muons that do not have tracks in **MS**, the **ID** track is matched with the calorimeter's minimum ionisation energy loss signals. If a match is found, the parameters of the **ID** track are used directly for muon reconstruction.

The main goal of muon identification is to discriminate against non-prompt muons from hadronic decays and heavy-flavor hadrons. The input variables for muon identification include:

1. **Track Requirements:** Hits in **ID** and short segments in **MS**.
2. **Matching between ID and MS Tracks:** Matching Quality described by  $q/p$  and  $p_T$  measurements.
3. **Track Fitting Parameters:** This involves the fitting of tracks in the **ID** and **MS** hits, usually calculated using normalized  $\chi^2$  tests.
4. **Vertex Requirements:** Precision in vertex measurement ( $|d_0|/\sigma(d_0) < 3$  and  $|z_0 \sin \theta| < 0.5$  mm).

These requirements define five commonly used muon working points: Loose, Medium, Tight, High- $p_T$ , and Low- $p_T$ . Further details about muon identification and reconstruction can be found in Ref. [90].

### 3.5.4 Jets

Quarks and gluons are always found in a clustered state, making them impossible to detect in detectors directly. So, the question arises: how do we measure hadronic final states? The solution lies in calculating a combined bundle of particles, and we reconstruct these composite objects in  $(\eta, \phi)$  space known as jets.

---

<sup>9</sup>**MS** segment refers to a short section of a track formed from hits in a single layer or station of the **MS**, rather than a complete track through the full spectrometer.

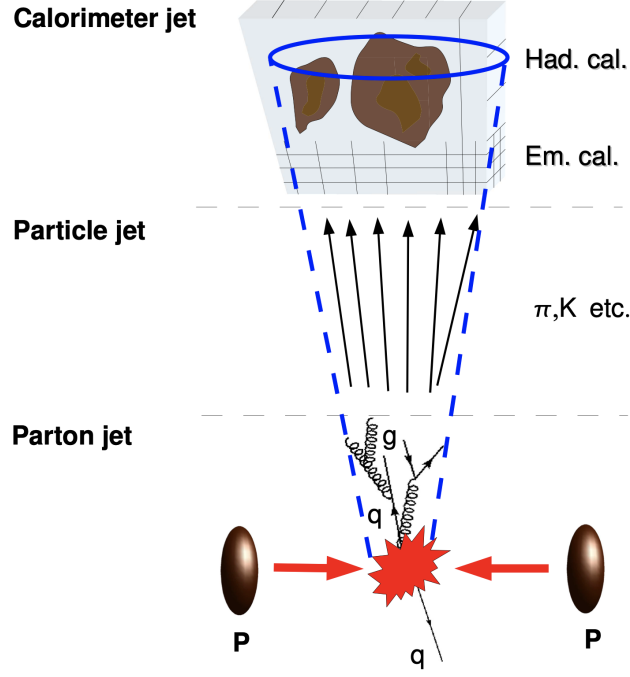


Figure 3.13: The evolution of a partonic jet from hard scattering to hadronization, forming particle jets, which are then measured as calorimeter jets in the ATLAS detector. The calorimeter detects energy deposits in both the calorimeters [52].

### Jet reconstruction

The **ATLAS** detector employs a **particle flow (P-flow)** algorithm to accurately identify and reconstruct jets by integrating information from various detector components, such as the tracker and calorimeters. The **P-flow** algorithm identifies individual charged particles by matching tracks from the **ID** with energy deposits in the calorimeters. Using both tracker and calorimeter information provides a more precise measurement of each particle's momentum and energy, which feeds into the jet reconstruction process. Once the individual charged particles are reconstructed through **P-flow**, neutral energy deposits within the calorimeters are grouped into clusters using a topological cluster algorithm, as illustrated in Figure 3.13.

The procedure is as follows: It starts with a seed cell that has a signal-to-noise ratio above a predefined threshold  $t_{\text{seed}}$ . Then, neighboring cells with signal-to-noise ratios above a lower threshold  $t_{\text{cell}}$  are added iteratively to form a cluster. To further enhance the cluster, neighboring cells with signal-to-noise ratios above another threshold  $t_{\text{neighbour}}$  are added. Finally, clusters with positive energy are selected.

These clusters, along with the individual particles identified by the **P-flow** algorithm, serve as inputs for the jet-finding algorithms. These algorithms are then applied to combine these inputs into jets. These algorithms need to be safe from collinear and infrared divergences. For instance, the definition of a reconstructed jet shouldn't depend on soft or collinear glu-

ons. Moreover, these algorithms should be easily implementable in theoretical calculations and experimental analysis. Cone algorithms are among the most popular.

The **ATLAS** detector uses an algorithm known as the anti-kt algorithm. This algorithm is safe from both infrared and collinear divergences [91]. These algorithms measure the distance between two objects, and pairs are identified based on the minimum distance. If the distance between them is below a certain threshold, they are merged into *pseudojets*. This process continues until no more merging is possible, and at this stage, all pseudo jets are assigned the status of jets. To understand these algorithms, let's start with  $i$  as an iterative number for each pseudo jet, defining a jet-jet distance as

$$d_{ij} = \min(d_i, d_j) \frac{\Delta R_{ij}^2}{R^2} \quad (3.6)$$

where  $d_i$  is a jet-beam distance given as  $d_i = P_{T_i}^2$ ,  $R$  is the size of jet in  $(\eta, \phi)$  space and  $\Delta R$  is the angular separation between two jets. Minimise the set of  $d_{ij}$  and  $d_i$  and call it  $d_{min}$ ;

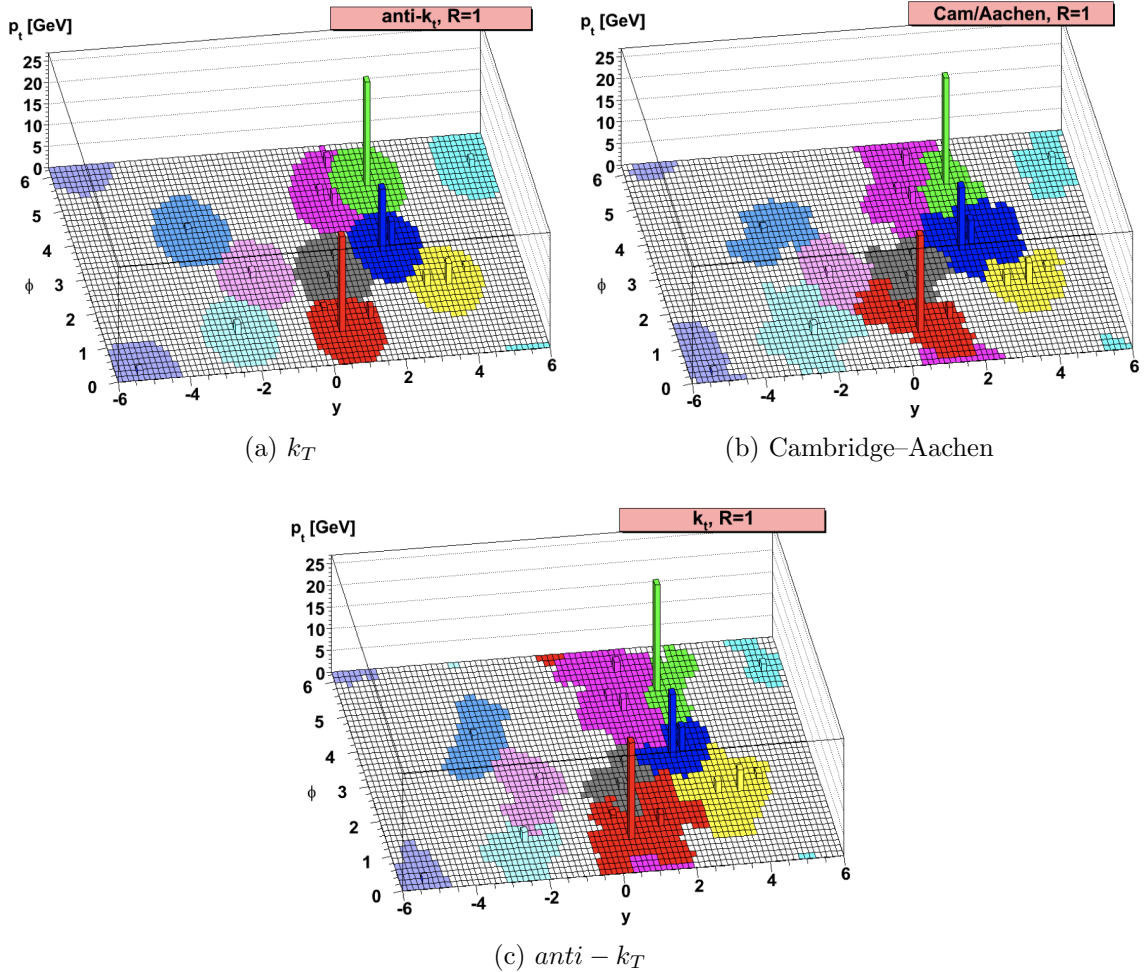


Figure 3.14: A parton-level Monte Carlo simulated event sample that shows the regions and forms of the hard jets that result for  $R = 1$ , taken from Ref. [91].

if  $d_{min}$  belongs to the set of  $d_i$ , then one pseudojet is not mergeable and further will not part in calculation and call as a jet. Similarly, if  $d_{min}$  belongs to the set of  $d_{ij}$ , then two pseudo jets are mergeable and taken as further input with symbol say  $k$ . This process is repeated until no further merging is possible, meaning no pseudojets remain unprocessed. The parameter  $P$  has value -1,0,+1 and depends upon the choice of algorithm, i.e., if  $P = -1$  (choice is anti- $k_T$ ), if  $P = 0$  (choice is Cambridge–Aachen), if  $P = +1$  (choice is  $k_T$ ). Figure 3.14 visually depicts all three algorithms to the same event [91].

## Jet calibration

Pile-up contamination significantly affects jet reconstruction because it mainly consists of low-energy hadronic behaviour that can interfere with calorimeter signals from hard scatter jets. Various techniques are available to reduce pile-up by subtracting its effects from individual jet inputs. One such method, called the **Jet Vertex Tagger (JVT)**, uses tracking data to determine the likelihood that a jet comes from the hard scatter ( $JVT = 1$ ) or from pile-up ( $JVT = 0$ ). The rejection of pile-up jets can be improved by setting specific requirements on the jet's **JVT**. Additionally, in the forward region, a **JVT** is used to identify hard scatter and pile-up jets [92].

The energy of a jet is determined by adding up the energy deposited in the cells of the hadronic calorimeter. This measurement needs adjustment for several factors, such as dead material<sup>10</sup>. The **Monte Carlo Simulations (MC)** provides energy corrections based on the jet's  $P_T$  and  $\eta$ . Topological clusters are categorized based on composition and expected origin using the calibration method of the **Local cluster weighting (LCW)**. The **LCW** method operates within the

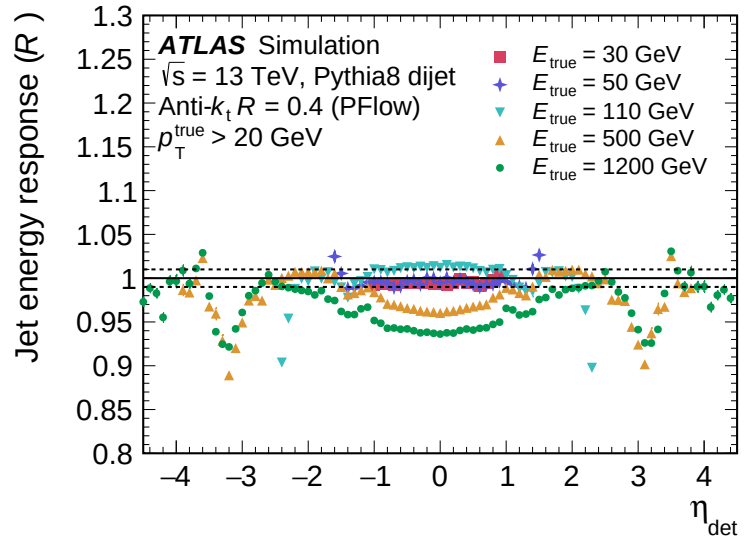


Figure 3.15: The jet energy response as a function of  $\eta_{det}$  for jets of truth energy of 30, 50, 110, 500, and 1200 GeV [93].

framework of topological cell clustering, where calorimeter cells are grouped into clusters based

<sup>10</sup>Dead material refers to substances that particles pass through but are outside the active region of the detector. Examples of such dead material include the solenoid magnet or the walls of the ECAL cryostat.

on their signal significance. The **LCW** method helps to differentiate clusters originating from **EM** activity, hadronic showers, or pile-up, allowing the correct energy scale to be applied [94]. Besides **LCW** corrections, another straightforward adjustment is the final jet energy calibration, also known as the *jet energy scale*, which links the calorimeter’s response to the actual jet energy, as shown in 3.15.

### b-jet tagging

Jets originating from bottom quarks are crucial in searches for new physics and play a key role in **ATLAS** physics studies. Bottom quark hadrons last longer in the detector, making it possible to identify them using tracking and vertexing information. This process, called b-tagging, assigns a jet as originating from a b-quark hadron. Nowadays, an artificial neural network technique is used to classify the flavour of jets, based on features like tracking data, displaced vertices, jet shape, transverse momentum, and soft leptons from bottom quark decays. These inputs allow the networks to effectively distinguish b-jets from light-flavor jets [95, 96].

### 3.5.5 Missing transverse momentum

Once all detectable objects in a detector have been measured, we need to account for particles that cannot be directly detected, such as neutrinos. After accounting for all measurable objects, the remaining momentum in the plane transverse to the beam axis is known as missing transverse momentum. This missing transverse momentum represents the total momentum of all the invisible particles.

In this context, the missing transverse energy ( $E_T^{miss}$ ) is a key observable, representing the energy imbalance in the transverse plane. It is crucial for identifying particles like neutrinos or hypothetical **BSM** particles, such as the **LSP**. The accurate reconstruction of  $E_T^{miss}$  plays a central role in searching for new physics.

However, missing transverse energy doesn’t only reflect invisible particles; it can also include fake components, such as those that couldn’t be reconstructed correctly. Missing transverse energy is measured using the energy deposited in calorimeters and the muons detected in the **MS**. To measure missing transverse energy, criteria are applied to visible objects, such as applying transverse momentum cuts, and it is calculated as follows:

$$E_{T,x,y}^{miss} = E_{T,x,y}^{miss,e} + E_{T,x,y}^{miss,\gamma} + E_{T,x,y}^{miss,\tau} + E_{T,x,y}^{miss,jets} + E_{T,x,y}^{miss,SoftTerm} + E_{T,x,y}^{miss,\mu} \quad (3.7)$$

each term represents the negative total of the objects’ transverse energy used to compute it



along the x and y-axis. So, the above equation can also be written as:

$$-E_T^{\text{miss}} = \sum_e \vec{p}_T + \sum_\gamma \vec{p}_T + \sum_\tau \vec{p}_T + \sum_\mu \vec{p}_T + \sum_j \vec{p}_T + \sum_{\text{soft}} \vec{p}_T \quad (3.8)$$

However, a notable term here is the *SoftTerm*, which can appear in two forms: track soft terms and cluster soft terms. Track soft terms consist of tracks originating from the primary vertex but not associated with any specific object. The **P-flow** algorithm utilises these tracks to account for low-energy charged particles that the calorimeter may miss. On the other hand, cluster soft terms refer to energy deposits in the calorimeter that are not linked to any reconstructed physics objects. The **P-flow** algorithm uses these clusters to account for neutral particles and energy deposits missed by the tracking system.

The *SoftTerm* plays a crucial role in **P-flow** by combining track-based and cluster-based data to enhance the reconstruction of missing transverse momentum. By incorporating these soft terms, the **P-flow** method effectively reduces pile-up effects and improves the overall precision of  $E_T^{\text{miss}}$ .

## 3.6 Event generation and detector simulation

---

In the **ATLAS** detector, a particle collision produces information about the characteristics and interactions of subatomic particles. Each collision typically results in a single recorded event. In **ATLAS** analysis, the information from these events is called “Data”.

Interpreting data and comparing it to theoretical predictions, often referred to as “Monte Carlo simulations” **MC**. Generating **MC** data is handled by the **ATLAS** simulation framework. Monte Carlo generators like MadGraph [97] and Pythia [98] are used to produce “truth events” because they are created without the effects of the detector.

Furthermore, to study the impact of the detector, we analyze how each particle deposits its energy in different parts of the detector for every event. To achieve this, we pass the generated events through Geant4 simulation [99], which models the interactions of particles with the detector materials. After the simulation step, the digitization step occurs, in which the simulated signals convert into a format that closely resembles the actual collision data. This process also accounts for pile-up effects, ensuring the simulation matches real experimental conditions as closely as possible. In many instances, a fast simulation of **ATLAS** is performed using **ATLFASTII**. This method utilises full Geant4 simulation for the **ID** and **MS** while employing **FASTCALOSIM** for the calorimeter. **FASTCALOSIM** smears the truth-level information, signif-



icantly reducing the required CPU time for simulating events, particularly those used in **BSM** searches.

### 3.7 ATLAS Software Releases

---

The **ATLAS** experiment depends on sophisticated software to manage and analyze the vast data generated by particle collisions. Central to this process, the Athena software framework evolves through sequential releases, with each version introducing improvements over its predecessor. Two notable releases, **ATLAS rel21: Release 21 of the ATLAS computing release (rel21)** and **ATLAS rel22: Release 22 of the ATLAS computing release (rel22)**, mark significant milestones aligned with different operational phases of the **LHC** [100–102].

The **ATLAS rel21** was primarily designed to support **LHC** operations during Run 2 from 2015 to 2018, while rel22 aligns with Run 3. This thesis focuses on analyses conducted using **ATLAS** Run 2, reprocessed Run 2, and early Run 3 data, primarily using rel22, with some comparative results between **rel21** and **rel22** electron reconstruction efficiencies in chapter 4.

The primary function of **rel21** was to process and analyze data gathered during the Run 2 period using the available detector configuration and computational resources.

In 2021, **rel22** was introduced, marking a significant leap in capability and technology. This version coincided with the transition to Run 3 of the **LHC**, which began in 2022. It was developed to accommodate the more challenging operational conditions of the upgraded **LHC**, including higher collision energies and luminosities. **rel22** has been extensively used for reprocessing both Run 2 **MC** simulations and data and new Run 3 data and **MC** simulations. Reprocessing Run 2 data with **rel22** became necessary to align with updated analysis requirements and integrate substantial improvements that had emerged in the software framework since the original data collection. This reprocessing enhanced the consistency and quality of the datasets used in physics analysis, particularly as Run 3 began, characterized by more complex collision events and higher luminosity.

A significant innovation introduced in **rel22** is the implementation of the *AthenaMT* framework, which enables multithreading. This feature allows multiple events to be processed parallel, improving resource utilization efficiency. By optimizing computational performance, **rel22** ensures that the **ATLAS** experiment can manage the increased data complexity expected in a high-luminosity environment like that of Run 3. In addition, **rel22** incorporates substantial updates to core algorithms, such as those involved in *tracking* [103] and *particle reconstruction*. These enhancements are crucial for improving the precision of physics measurements.

The transition from **rel21** to **rel22** reflects the ongoing development of **ATLAS**'s software infrastructure in response to the experiment's evolving data analysis needs.

## 3.8 Summary

---

In summary, the **ATLAS** detector at the **LHC** is a crucial tool for exploring the fundamental nature of matter. This chapter explains the **ATLAS** detector at the **LHC** at **CERN**, covering its both significance and capabilities. The chapter further explores the reconstruction of physics objects in the detector. A vital performance of the **ATLAS** detector is presented in the plot 3.16 taken from Ref. [69]. This plot summarises the **SM** production cross-section measurements from **ATLAS**, comparing data collected at different energy levels (5, 7, 8, and 13 TeV) with theoretical predictions. The plot includes measurements of various processes illustrating the agreement between observed data and theoretical models within the uncertainties.

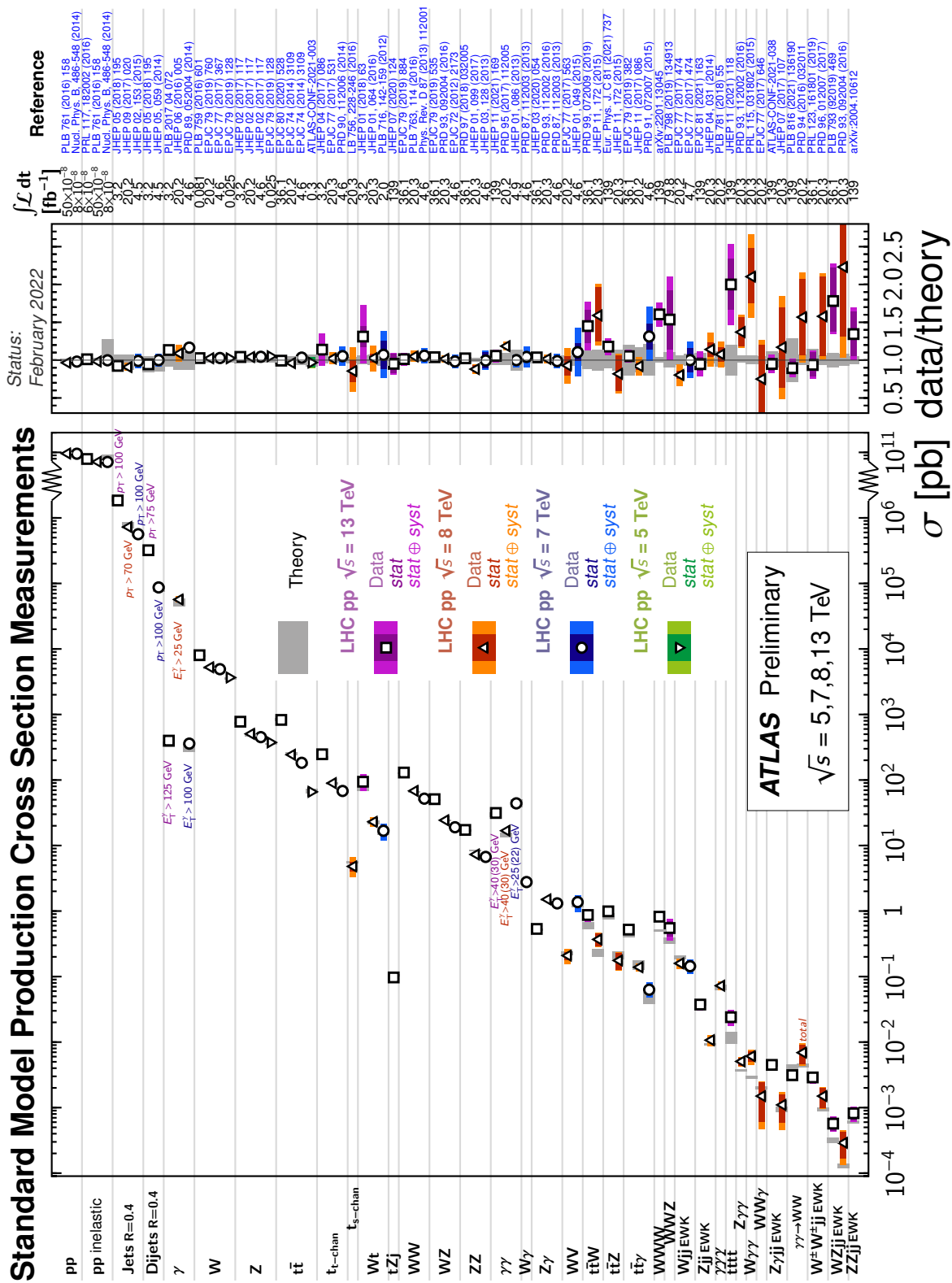


Figure 3.16: Various measurements of the total and fiducial production cross-sections under the Standard Model, together with a comparison of the measurements to the theoretical values, are summarised [69].

# Chapter 4

## Electron reconstruction efficiencies studies

### Contents

---

|            |                                                                                                                       |           |
|------------|-----------------------------------------------------------------------------------------------------------------------|-----------|
| <b>4.1</b> | <b>Context and Motivation</b> . . . . .                                                                               | <b>54</b> |
| <b>4.2</b> | <b>Measurement Methodology</b> . . . . .                                                                              | <b>55</b> |
| 4.2.1      | Tag and probe method . . . . .                                                                                        | 56        |
| 4.2.2      | Event and Object selection . . . . .                                                                                  | 57        |
| 4.2.3      | Electron Reconstruction Efficiency . . . . .                                                                          | 58        |
| 4.2.4      | Background Evaluation . . . . .                                                                                       | 60        |
| 4.2.5      | Uncertainties . . . . .                                                                                               | 62        |
| <b>4.3</b> | <b>Discussion on results</b> . . . . .                                                                                | <b>64</b> |
| 4.3.1      | Efficiency and Scale Factors measurements with ATLAS reprocessed<br>Run 2 data and corresponding MC samples . . . . . | 64        |
| 4.3.2      | Efficiency and Scale Factors measurements with ATLAS early Run<br>3 data and corresponding MC samples . . . . .       | 71        |
| <b>4.4</b> | <b>Summary</b> . . . . .                                                                                              | <b>76</b> |

---

In this chapter, I will present my own results obtained with the pre-existing methodology documented in Refs. [104–106]. The construction, improvements, and operation of the **ATLAS** detector depend on an extensive collaboration. In this collaboration, one must complete a qualification task to achieve Qualified Author status and become part of the list of authors on **ATLAS** publications. This chapter presents the results obtained from this task, which was carried out within the combined  $e/\gamma$  performance group during the first year of my PhD. I worked on measuring the electron reconstruction efficiencies within the **ATLAS** detector. **My own results presented in this chapter are contained in an ATLAS internal note [107] of which I am the only author.**

## 4.1 Context and Motivation

---

The electron is a stable particle, and one of the crucial components in **ATLAS** searches for both the **SM** and **BSM**. Hence, it is essential to measure electrons with high precision. In addition, high-precision measurements require excellent control of the efficiency uncertainties since they can be a limiting factor highlightciteaad2016measurement. In the **ATLAS** detector, electrons<sup>1</sup> are reconstructed using hits in different layers of the tracking detector, associated with a narrow cluster of energy deposits in the **ECAL**. The positions in each layer, along with the measured energies per layer and shower profiles, are recorded with high-precision and using advanced techniques to reduce pile-up and noise contribution. Despite this precision, a significant challenge remains in identifying high-efficiency electrons because jets or photons can be misidentified as electrons (called fakes). Additionally, electrons from non-prompt sources, such as photon conversions, semi-leptonic heavy-flavour decays, and decays of charged pions, are the main backgrounds and create significant challenges in maintaining high electron reconstruction efficiency while ensuring the purity of the selected electrons.

To address the above challenges, this chapter will explain the tag-and-probe method to calculate the electron reconstruction efficiency within the **ATLAS** detector. The measurements of electron reconstruction efficiency are made using data recorded with the **ATLAS** detector from 2015 to 2018 at a center-of-mass energy of  $\sqrt{s} = 13$  TeV. The measurements are compared to expectations from **MC**. The tag-and-probe method is employed to achieve this, utilizing the  $Z \rightarrow e^-e^+$  event topology. The TagandProbe framework developed in recent years within the **ATLAS** collaboration, specifically designed to measure various efficiencies such as reconstruction, isolation and identification, is used for this purpose. This framework is applied to physics

---

<sup>1</sup>No separate reconstruction efficiency measurements for electrons and positrons were performed

processes like  $Z \rightarrow e^-e^+$  and  $J/\psi \rightarrow e^-e^+$ . For further details, see Ref. [108]. The complete methodology of the measurement is described in Section 4.2, while a detailed discussion of my results is provided in Section 4.3.

## 4.2 Measurement Methodology

---

The efficiency ( $\epsilon$ ) represents the fraction of electron candidates emitted within the active detector volume that satisfy the selection criteria. This overall efficiency can be factorized into different components, each measured separately. Specifically, the total efficiency for a single electron can be expressed as the product of five efficiencies: the **EM** cluster reconstruction efficiency ( $\epsilon_{\text{EMclus}}$ ), electron reconstruction efficiency ( $\epsilon_{\text{reco}}$ ) (which is our main focus and as described in section 4.2.3), identification efficiency ( $\epsilon_{\text{id}}$ ), isolation efficiency ( $\epsilon_{\text{iso}}$ ), and trigger efficiency ( $\epsilon_{\text{trig}}$ ). The **EM** cluster reconstruction efficiency,  $\epsilon_{\text{EMclus}}$ , is measured using **MC** simulations, ensuring that the reconstructed cluster is associated with a genuine electron produced at the generator level. For electrons with transverse energy ( $E_T$ ) greater than 10 GeV,  $\epsilon_{\text{EMclus}}$  is found to be above 99%, indicating a high reconstruction efficiency. The total efficiency is given as:

$$\epsilon_{\text{total}} = \epsilon_{\text{EMclus}} \times \epsilon_{\text{reco}} \times \epsilon_{\text{id}} \times \epsilon_{\text{iso}} \times \epsilon_{\text{trig}} = \frac{N_{\text{cluster}}}{N_{\text{all}}} \times \frac{N_{\text{reco}}}{N_{\text{cluster}}} \times \frac{N_{\text{id}}}{N_{\text{reco}}} \times \frac{N_{\text{iso}}}{N_{\text{id}}} \times \frac{N_{\text{trig}}}{N_{\text{iso}}} \quad (4.1)$$

where  $N_{\text{all}}$  is the total number of produced electrons,  $N_{\text{clus}}$  stands for the number of reconstructed **EM** clusters,  $N_{\text{reco}}$  is the number of reconstructed electrons with a good track quality.  $N_{\text{id}}$  is the number of reconstructed and identified electron candidates.  $N_{\text{iso}}$  is the number of electron candidates satisfying the reconstruction, identification, and isolation requirements.  $N_{\text{trig}}$  is the number of electrons passing, reconstruction, identification, isolation, and trigger requirements.

The efficiencies depend upon the interactions of electron candidates with the detector. These interactions are characterized by the electron's energy  $E_T$  and pseudorapidity  $\eta$ . Therefore, the efficiencies are measured separately for different ranges of  $E_T$  and  $\eta$ , as detailed in Tables 4.1 and 4.2 respectively. The specific ranges and bin boundaries are chosen based on several considerations. The energy bins start at 15 GeV because the reconstruction efficiency measurement below this energy becomes unreliable due to large backgrounds. The upper limit of 150 GeV accommodates higher-energy electrons while still ensuring accurate efficiency measurement.

For  $|\eta|$ , the binning is driven by the detector’s geometry. For instance, there is a transition region between the **EM** barrel and endcap detectors at  $1.37 < |\eta| < 1.52$ . The acceptance of the presampler only extends up to  $|\eta| < 1.81$ , and at  $|\eta| = 2.37$ , the granularity of the detector’s calorimeter strips changes to a coarser configuration, which degrades the tracking performance at the very edge of the **ID**. By aligning the bin ranges and widths with these considerations, the measurement of electron reconstruction efficiency is optimized to reflect the detector’s capabilities and ensure accurate and meaningful results.

| Bin boundaries in $E_T$ [GeV] |    |    |    |    |    |    |    |    |    |     |
|-------------------------------|----|----|----|----|----|----|----|----|----|-----|
| 15                            | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 60 | 80 | 150 |

Table 4.1: Measurement bins in electron transverse energy  $E_T$ .

| Bin boundaries in $\eta$ |       |       |       |       |       |       |       |       |      |      |      |
|--------------------------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|------|
| -2.47                    | -2.37 | -2.01 | -1.81 | -1.52 | -1.37 | -1.15 | -0.08 | -0.60 |      |      |      |
| -0.10                    | 0     | 0.10  | 0.60  | 0.80  | 1.15  | 1.37  | 1.52  | 1.81  | 2.01 | 2.37 | 2.47 |

Table 4.2: Measurement bins in electron pseudo-rapidity  $\eta$ .

To start computing efficiencies, any contributions from the background need to be subtracted, described in section 4.2.4. The truth information is used in **MC** simulations to estimate background. Different approaches are used for data.

### 4.2.1 Tag and probe method

The principle of the tag-and-probe method is that strict requirements are applied on one of the electron candidates named **tag** and Loose selection criteria are used on other candidate named **probe** while their invariant mass should be close to the decaying resonance mass, i.e., in our case the mass of Z boson  $m_z \approx 91$  GeV. This allows for strong suppression backgrounds to the measurement while avoiding selection bias for the probe candidates, with which the efficiency measurement is performed. The efficiency and scale factors<sup>2</sup> measurements are taken within the range  $15 < E_T < 150$  GeV. Below 15 GeV, the scale factor is set to 1 [89] because it is not accessible in data measurements, and uncertainty of 2% (5%) in the barrel (endcap) is applied to conservatively address the range of values and uncertainties in the scale factors for low  $E_T$  measurements, while above 150 GeV, the values from the highest measurement bin are used [89]. Every electron candidate pair is evaluated for tag-probe selections, which means having multiple probes within the same event is possible.

<sup>2</sup>The scale factor is calculated as a ratio of efficiency from data to the efficiency from MC simulation, for the ultimate purpose of being applied as a correction factor to any simulated physics process.

### 4.2.2 Event and Object selection

Events are selected based on several trigger requirements, initially specified in Table 4.3, which vary according to the data-taking year. These triggers are utilized for the initial event selection. Subsequently, events undergo further refinement using single-electron triggers, which also vary based on the data-taking year. For example, from 2015 to mid-2016, electrons were required to have an energy threshold of 24 GeV. This threshold increased to 26 GeV from mid-2016 until the end of that year. In 2017 and 2018, the criteria further evolved, requiring Tight identification and Loose isolation conditions [89]. At the event level, one primary vertex<sup>3</sup>, including at least two tracks, is required. Additionally, at least two electron candidates, originating from either the electron or photon container, are necessary. During object-level selection, strict criteria are applied to the **tag** electron, which must have a transverse energy  $E_T > 25$  GeV. Furthermore, the **tag** electron is required to lie within the central region of the detector ( $|\eta| \leq 2.47$ ) but outside the transition region between the barrel and endcap of the **ECAL** ( $1.37 < |\eta| < 1.52$ ). In addition to this, the **tag** electron must pass the tight likelihood identification criteria and meet the requirements for good object quality. In the simulation, the reconstructed electron candidate is also required to originate from the generated  $Z \rightarrow e^+e^-$  decay (“truth-matched”).

| For year | Triggers                                                                                                                    |
|----------|-----------------------------------------------------------------------------------------------------------------------------|
| 2015     | HLT_e24_lhmedium_L1EM20VH<br>HLT_e60_lhmedium<br>HLT_e120_lhloose                                                           |
| 2016     | HLT_e24_lhtight_nod0_ivarloose<br>HLT_e60_lhmedium_nod0<br>HLT_e140_lhloose_nod0<br>HLT_e300_etcut                          |
| 2017     | HLT_e26_lhtight_nod0_ivarloose<br>HLT_e60_lhmedium_nod0<br>HLT_e140_lhloose_nod0<br>HLT_e300_etcut                          |
| 2018     | HLT_e26_lhtight_nod0_ivarloose<br>HLT_e60_lhmedium_nod0<br>HLT_e140_lhloose_nod0<br>HLT_e300_etcut                          |
| 2022     | HLT_e26_lhtight_ivarloose_L1EM22VHI<br>HLT_e60_lhmedium_L1EM22VHI<br>HLT_e140_lhloose_L1EM22VHI<br>HLT_e300_etcut_L1EM22VHI |

Table 4.3: Triggers used for the measurements.

---

<sup>3</sup>PV: Vertex with the largest sum of  $P_T^2$  from associated tracks.



Probe electrons must satisfy specific selection criteria, whether they have an associated track or are trackless (**referred to as photons**). A probe must have a transverse energy  $E_T > 15$  GeV and be located within the central region of the detector, where  $|\eta| \leq 2.47$ . Additionally, electron probes used in the numerator must meet track quality criteria, which require the associated track to have at least seven precision hits from the SCT and pixel detectors, including at least one hit from the pixel detector. Probes must also satisfy good object quality standards and be isolated by  $\Delta R > 0.4$  from any reconstructed jet. Similar to the **tag**, the **probe** is also required to be truth-matched for **MC**. Due to the lack of a reconstructed track, truth matching for the photon probe is more primitive. It is conducted by ensuring that the distance in the  $\Delta R$  parameter between the reconstructed and truth-level electron is less than or equal to 0.2 ( $\Delta R \leq 0.2$ ).

Additionally, a separation criterion is applied to distinguish the photon probe from nearby electrons, requiring that the distance  $\Delta R$  between the photon and any nearby electron is greater than 0.15 ( $\Delta R > 0.15$ ). This helps prevent cases where the same cluster might be erroneously reconstructed as an electron and a photon. However, such instances should be avoided if photons with `author=ambiguous` are not retained. The selection criteria for both the **tag** and **probe** objects are detailed in Table 4.4.

The invariant mass of the **tag-probe** system is required to be within the range of the Z boson mass, specifically  $75 < m_{ee} < 105$  GeV. No charge requirements are applied. In cases where multiple probe candidates are present, only those with a pair invariant mass matching the tag will be selected. As a result, a single event can contribute multiple **tag-probe** pairs to the measurement, leading to a multiplicity greater than one [109].

### 4.2.3 Electron Reconstruction Efficiency

The reconstruction efficiency is the ratio of electron probes that pass the track and object quality requirements over the total number of reconstructed clusters in the **ECAL** corresponding to a true electron. This efficiency reflects how accurately tracks are reconstructed and matched to **EM** clusters. The track quality criteria are based on the total number of hits across all silicon detectors, with at least one hit required in the pixel detector. The reconstruction efficiency can be expressed as:

$$\varepsilon_{reco} = \frac{N_{pass}^{sig}}{N_{pass}^{sig} + N_{fail}^{sig}} = \frac{N_p^e - B_p^e}{(N_p^e - B_p^e) + (N_F^e - B_F^e) + (N_\gamma - B_\gamma)} \quad (4.2)$$

where  $N_p^e$  and  $N_F^e$  are the number of electron probes passing/failing track quality and object quality for numerator requirements, and  $B_p^e$  and  $B_F^e$  are corresponding background terms.  $N^\gamma$  denotes the number of particles reconstructed only as photons (i.e. probes with no matched track, referred to as photons, or **EM** clusters with no associated track), and  $B^\gamma$  represents its associated background [110]. The invariant mass distribution of electron pairs in the numerator and denominator are shown in Figure 4.1.

| <b>Tag</b>                                                 | <b>Probe</b> (Electron/Photon)                            |
|------------------------------------------------------------|-----------------------------------------------------------|
| TightId (baseline)                                         | Distinct from the tag electron                            |
| $ \eta  \leq 2.47$ (Veto<br>$1.37 \leq  \eta  \leq 1.52$ ) | $ \eta  \leq 2.47$                                        |
| $E_T \geq 25$ GeV                                          | $E_T \geq 15$ GeV                                         |
| Pass Object Quality (OQ) <sup>a</sup>                      | Pass OQ & Track Quality(Only at Numerator)                |
| Trigger Matched                                            | Jet Veto with $\Delta R < 0.4$                            |
| Truth matched to Z (MC Only)                               | Truth matched to Z (MC Only)                              |
| Pass Author (Electron,<br>Ambiguous <sup>b</sup> )         | Pass Author (Electron, Ambiguous)                         |
|                                                            | Pass Author (Photon)                                      |
|                                                            | to true electron $\leq 0.2$ (Photon MC Truth<br>Matching) |
|                                                            | $\Delta R$ (photon probe, any e) $> 0.15$ <sup>c</sup>    |

<sup>a</sup> A cluster that is not affected by the presence of a dead front-end board in the first or second sampling (i.e., an electronic board in the calorimeter that is not processing signals properly), a dead high-voltage (HV) region affecting the three layers of the electromagnetic calorimeter (i.e., a region where the high-voltage supply is non-functional and causes loss of signal across all layers), or by the presence of a masked cell in the core (i.e., a cell that has been excluded from use due to known issues or calibration problems) is considered reliable for analysis [111].

<sup>b</sup> EGamma Ambiguity Selection addresses the challenge of distinguishing objects that exhibit electron and photon characteristics. This ambiguity arises when the same cluster meets the criteria for both electron and photon selections. The selection process involves applying specific criteria to resolve this ambiguity, ensuring that each object is accurately classified.

<sup>c</sup> The minimum  $\Delta R$  requirement between the photon and the closest-by electron, where  $\Delta R$  is defined as  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ . Any value can be set to select this requirement in the TagAndProbe framework [109].

Table 4.4: Object level selections for **tag** and **probe** system

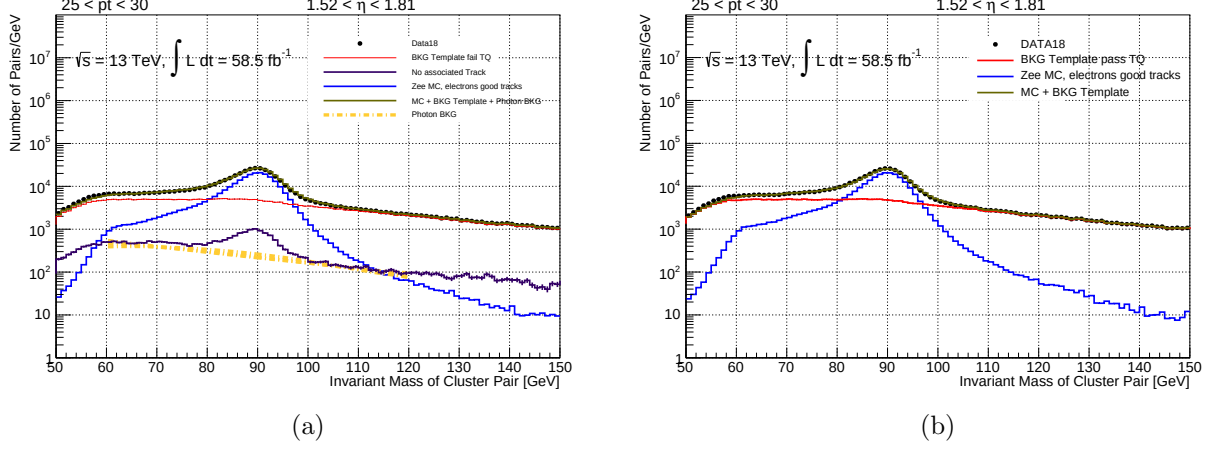


Figure 4.1: Invariant mass distributions of electron pairs in the denominator of equation 4.2 by taking failing Quality Track term and photon term(a) and the numerator(b) of the reconstruction efficiency. Background templates are normalized, and their variation1 is used, given in Table 4.5.

#### 4.2.4 Background Evaluation

The background cluster-pair (**tag-probe**) is extracted from the data by reversing the identification requirements applied to the probe object. The resulting distribution is then normalized to the background-dominated cluster-pair invariant mass distribution within the 110–250 GeV range.

##### Background template for electron candidates having an associated track

The background template for electron candidates with associated tracks is derived by inverting identification and isolation requirements. The background from the probes that pass/fail the track quality requirements, i.e.  $B_p^e$  and  $B_F^e$ , is estimated using templates. In recent studies, the *cut-based Loose* identification templates were used to estimate the backgrounds, but detailed research is done in Ref. [112, 113] where likelihood-based templates are given preference over *cut-based Loose* identification background templates for the measurements in **rel22** setup [102]. The background templates are made from observed data events. Two types of template variations are used in these measurements, and their selections are shown in Table no 4.5.

Normalization is performed in either high or low regions of the invariant mass distribution (considered signal-free). The remaining signal in the background template is subtracted using **MC** simulations.

The estimation of background coming from probes with track (either passing or failing track

quality conditions) can be given by the relation:

$$B_x^e = N_{peak,x}^{template} - N_{peak,x}^{templateMC} \times NF \times \frac{N_{tail,x}^e - N_{tail,x}^{MC} \times NF}{N_{tail,x}^{template} - N_{tail,x}^{templateMC} \times NF} \quad (4.3)$$

where NF(normalization factor) is the ratio of the number of probes with TightID baseline in the data in the high mass region of Z peak to the number of probes with TightID baseline in the **MC** simulations given as

$$NF = \frac{N_{peak}^{data}tight}{N_{peak}^{MC}tight}$$

Where  $x$  can be either passing or failing track quality conditions,  $B_x^e$  represents the number of background events in the signal region<sup>4</sup>.  $N_x^e$  and  $N_x^{template}$  are the total number of probes and the number of probes in the background template in data, respectively. Additionally,  $N_{peak}$  and  $N_{tail}$  refer to the Z peak and high/low mass control regions, respectively.  $N_{peak,x}^{template}$  is the number of probes in the background template in high mass region of Z peak which is subtracted using **MC** simulations refer to the term  $N_{peak}^{templateMC}$ .  $N_{tail,x}^e$  is the number of failing/passing quality track probes in the low mass region of Z peak.  $N_{tail}^{MC}$  is the number of probes from a Zee signal **MC**. Similarly, the denominator of equation 4.3 has the number of probes in the data background template in the low mass region of Z peak which is subtracted using **MC** simulations refer to the terms  $N_{tail,x}^{template}$  and  $N_{peak}^{templateMC}$  respectively.

| <b>Templates</b>  | <b>Inverted Cuts</b> | $E_T < 30 \text{ GeV}$           | $E_T \geq 30 \text{ GeV}$        |
|-------------------|----------------------|----------------------------------|----------------------------------|
| <b>Variation1</b> | fail likelihood      | $topoE_T^{cone30}/E_T > 0.02$    | $topoE_T^{cone30}/E_T > 0.02$    |
|                   | Ultraloose           | $120 < m_{ee} < 250 \text{ GeV}$ | $120 < m_{ee} < 250 \text{ GeV}$ |
| <b>Variation2</b> | fail likelihood      | $topoE_T^{cone40}/E_T > 0.05$    | $topoE_T^{cone40}/E_T > 0.05$    |
|                   | Veryloose            | $60 < m_{ee} < 70 \text{ GeV}$   | $120 < m_{ee} < 250 \text{ GeV}$ |

Table 4.5: Templates used for background estimation for electrons with track

### Background template for electron candidates having no associated track

For non-reconstructed electrons or photon probes (i.e. **EM** clusters that are matched with a true electron but are reconstructed as photons due to missing matched tracks), the background is estimated by fitting the sideband regions (defined in section 4.2.5) around the electron-photon invariant mass  $m$  distribution using a third-order polynomial function. The background estimation is then obtained by integrating the fitted function over the signal region. The fit is

<sup>4</sup>i.e., the interval where efficiency is measured (Z peak)

performed outside the signal region, specifically on two sidebands one at low mass and one at high mass—where the number of signal events is minimal, ensuring that they have a negligible impact on the background estimation. A more detailed explanation of this method is provided in Ref. [110].

## 4.2.5 Uncertainties

### Statistical uncertainty

The statistical uncertainty is computed using the error propagation formula [104, 105]. For this, Equation 4.2 is reformulated by separating all observables into independent components, which results in the following expression:

$$\varepsilon_{reco} = \frac{N_p^e - B_p^{Temp} \frac{B_{tail}^{Pass}}{B_{tail}^{TempPass}}}{N_p^e - B_p^{Temp} \frac{B_{tail}^{Pass}}{B_{tail}^{TempPass}} + N_F^e - B_F^{Temp} \frac{B_{tail}^{Fail}}{B_{tail}^{TempFail}} + \Gamma} \quad (4.4)$$

To make the notation the same as in Ref. [110], the above equation can be written as

$$\varepsilon_{reco} = \frac{P - T \frac{P_H}{T_H}}{P - T \frac{P_H}{T_H} + F - U \frac{F_H}{U_H} + \Gamma} \quad (4.5)$$

with  $P = N_p^e$ ,  $T = B_p^{Temp}$  (background template for passing probes),  $P_H = B_{tail}^{Pass}$ ,  $T_H = B_{tail}^{TempPass}$  and  $F = N_F^e$ ,  $U = B_F^{Temp}$  (background templates for failing probes),  $F_H = B_{tail}^{Fail}$ ,  $U_H = B_{tail}^{TempFail}$ .  $H$  represents the high mass region (outside the  $Z$  mass peak window).  $\Gamma$  is the number of non-reconstructed candidates (after background subtraction). Only statistically independent variables are used for error propagation.

$$\varepsilon_{reco} = \frac{U_H(ST_H - TS_H)}{U_H(ST_H - TS_H) + T_H(RU_H - UR_H) + \Gamma T_H U_H} \quad (4.6)$$

with  $S = P - T$ ,  $S_H = P_H - T_H$

and  $R = F - U$ ,  $R_H = F_H - U_H$

The statistical uncertainty associated to  $\varepsilon_{\text{reco}}$  is :

$$\begin{aligned} \Delta\varepsilon_{\text{reco}}^2 = & \frac{T_H^2 (ST_H - TS_H)^2}{(\text{denom})^4} \times [U^2 R_H^2 \Delta U_H^2 + U_H^2 (U_H^2 \Delta R^2 + U_H^2 \Delta \Gamma^2 + U^2 \Delta R_H^2 + R_H^2 \Delta U^2)] \\ & + \frac{U_H^2 (RU_H - UR_H + \Gamma U_H)^2}{(\text{denom})^4} \times [T^2 S_H^2 \Delta T_H^2 + T_H^2 (T_H^2 \Delta S^2 + T^2 \Delta S_H^2 + S_H^2 \Delta T^2)] \end{aligned} \quad (4.7)$$

In this context, "denom" represents the denominator on the right-hand side of  $\varepsilon_{\text{reco}}$  in equation 4.6. The term  $\Delta$  corresponds to the Poisson uncertainty of the associated variable. Calculating the  $\Delta\Gamma$  term is more intricate, as it involves  $\Gamma = N^\gamma - B^\gamma$ , with  $(\Delta\Gamma)^2 = (\Delta N^\gamma)^2 + (\Delta B^\gamma)^2$ . Here,  $\Delta N^\gamma$  is the Poisson uncertainty on the number of photon probes, while  $\Delta B^\gamma$  represents the statistical uncertainty of the background, derived from the fit. Since the sideband region and the peak region do not overlap, these uncertainties are uncorrelated.  $\Delta B^\gamma$  is calculated through error propagation using the number of events in each bin employed in the fit. This can be expressed as:

$$(\Delta B^\gamma)^2 = \sum_i \left( \frac{\partial B^\gamma}{\partial n_i} \right)^2 \times (\Delta n_i^{(\text{stat})})^2 \quad (4.8)$$

where  $\Delta n_i^{(\text{stat})}$  represents the Poisson uncertainty associated with the number of events in the  $i^{\text{th}}$  bin.

## Systematic uncertainties

Systematic uncertainties are determined by simultaneously introducing variations in the selection process.

**Tag identification variations:** Three different tag IDs are used: *Tight*, *Tight* with  $E_T^{\text{cone40}} < 5$  GeV, and *Medium* with  $E_T^{\text{cone40}} < 5$  GeV. These variations help adjust the composition and amount of background, such as the proportion of events with real isolated electrons from  $W/Z$ +jets and QCD events without genuine electrons.

**Z-mass peak window variations:** ]80, 100[, ]75, 105[ and ]85, 95[ GeV. These variations allow identification efficiency changes based on invariant mass, particularly in the low-mass region, which is rich in bremsstrahlung electrons.

**Two background template variations**, listed in Table 4.5, to modify the signal contamination proportions.

**Four variations in the electron-photon invariant mass range used for fitting the**

***photon background:***

$[70, 80] \cup [100, 110]$ ,  $[60, 80] \cup [100, 120]$ ,  $[50, 80] \cup [100, 130]$ , and  $[55, 70] \cup [110, 125]$  GeV are selected to ensure that the polynomial fit function accurately captures the shape of the background  $m_{\ell\ell}$  distribution.

Implementing all these variations leads to 72 possible combinations of efficiencies and scale factors. The overall efficiency and statistical uncertainties are derived as the average across these systematic variations, while the corresponding systematic uncertainty is the standard deviation of the 72 efficiency combinations.

## 4.3 Discussion on results

---

### 4.3.1 Efficiency and Scale Factors measurements with ATLAS reprocessed Run 2 data and corresponding MC samples

The efficiency measurements were performed for full reprocessed with **rel22** Run2 data using data samples given in Table A.1. The measurement of the efficiency in both data and **MC** and scale factors are depicted in Figure 4.2. Overall, the efficiency increases with  $E_T$ , starting from 95% at  $E_T = 15$  GeV (except in the crack region<sup>5</sup>), and reaches a plateau of 98% for both data and **MC**. The scale factors are consistent with unity for most measurement points, except in the crack region of lower  $E_T = 15$  GeV. The overall measured efficiencies with data and **MC** and scale factors for all  $E_T$  bins for years 2015+16, 2017, and 2018 are shown in Figure 4.3, 4.4 and 4.5 respectively.

### Efficiency and scale factor comparison between Rel22 and Rel21 in Tag and Probe framework

Efficiencies in the Tag and Probe framework are compared between **rel22** and **rel21**. The datasets utilized for this analysis are listed in Table A.2. The main changes in **rel22** with respect to **rel21** as explained in Ref. [114] are

- Electron and Photon reconstruction is now fully based on topocluster, impacting the efficiencies of both particles.
- Improved classification between Electrons and Photons.

---

<sup>5</sup>The "crack region" in the ATLAS detector refers to the range  $1.37 < |\eta| < 1.52$ , where there is reduced detector coverage and sensitivity due to the transition between the barrel and endcap calorimeters.

- Changes in tracking, such as the number of Silicon hits, influence both electron and photon reconstruction.
- Central electron tracks no longer require a pixel hit, directly affecting electron reconstruction efficiency.
- The reconstruction of central  $e/\gamma$  is now split into 8 algorithms in **rel22**, while in **rel21**, it was a single one.

Figure 4.6 shows the measured data and **MC** efficiencies and scale factors. The black points show the measurements for **rel21** and red for **rel22**. Overall, the electron reconstruction efficiencies are consistently high across the dataset. When comparing the two software releases, **rel21** and **rel22**, the efficiencies appear slightly higher for **rel21** than for **rel22**. Still, the comparison looks closer, except for the transition region, i.e.,  $1.37 < |\eta| < 1.52$  of low  $E_T = 15$  GeV for both data and **MC** efficiencies. The total uncertainties are shown with the error bars. The scale factors' comparison ratio appears to be appropriate as well.



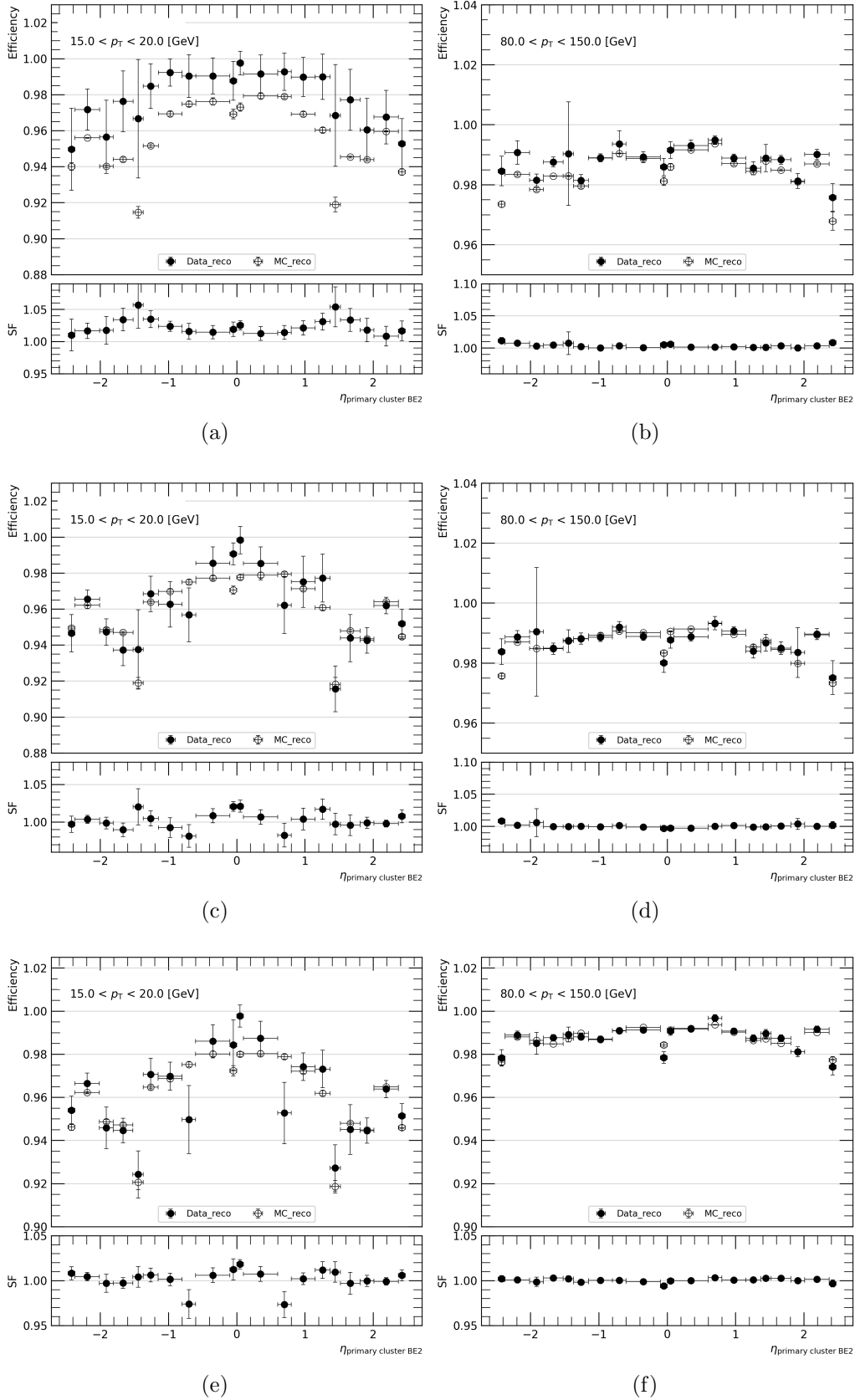


Figure 4.2: The plots a(b) for the 2015+16 data, c(d) for the 2017 data, and e(f) for the 2018 data, show the comparison between the data efficiency and MC efficiency in the low  $E_T$  range,  $15 < E_T < 20$  GeV, and in the high  $E_T$  range,  $80 < E_T < 150$  GeV. The lower panel illustrates the **Scale Factors** for the respective bins. The error bars reflect the total uncertainties, incorporating both statistical and systematic contributions.

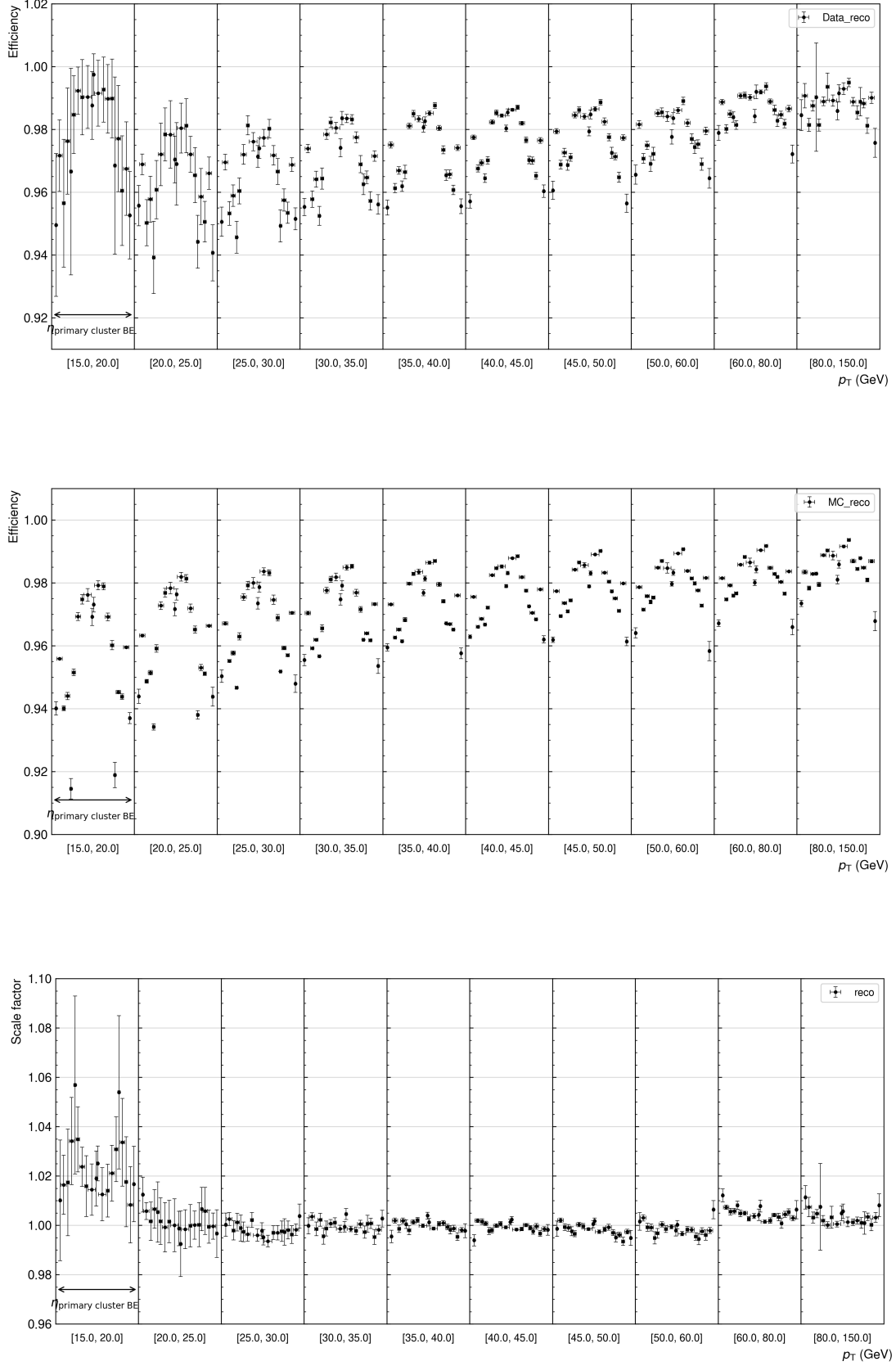


Figure 4.3: The plots for 2015+16 data where the first and second plot shows the overview of the data and MC efficiencies as a function of  $E_T$  and  $\eta$  bins (where  $\eta_{\text{primary cluster BE2}}$  refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of  $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of  $E_T$  and  $\eta$ .

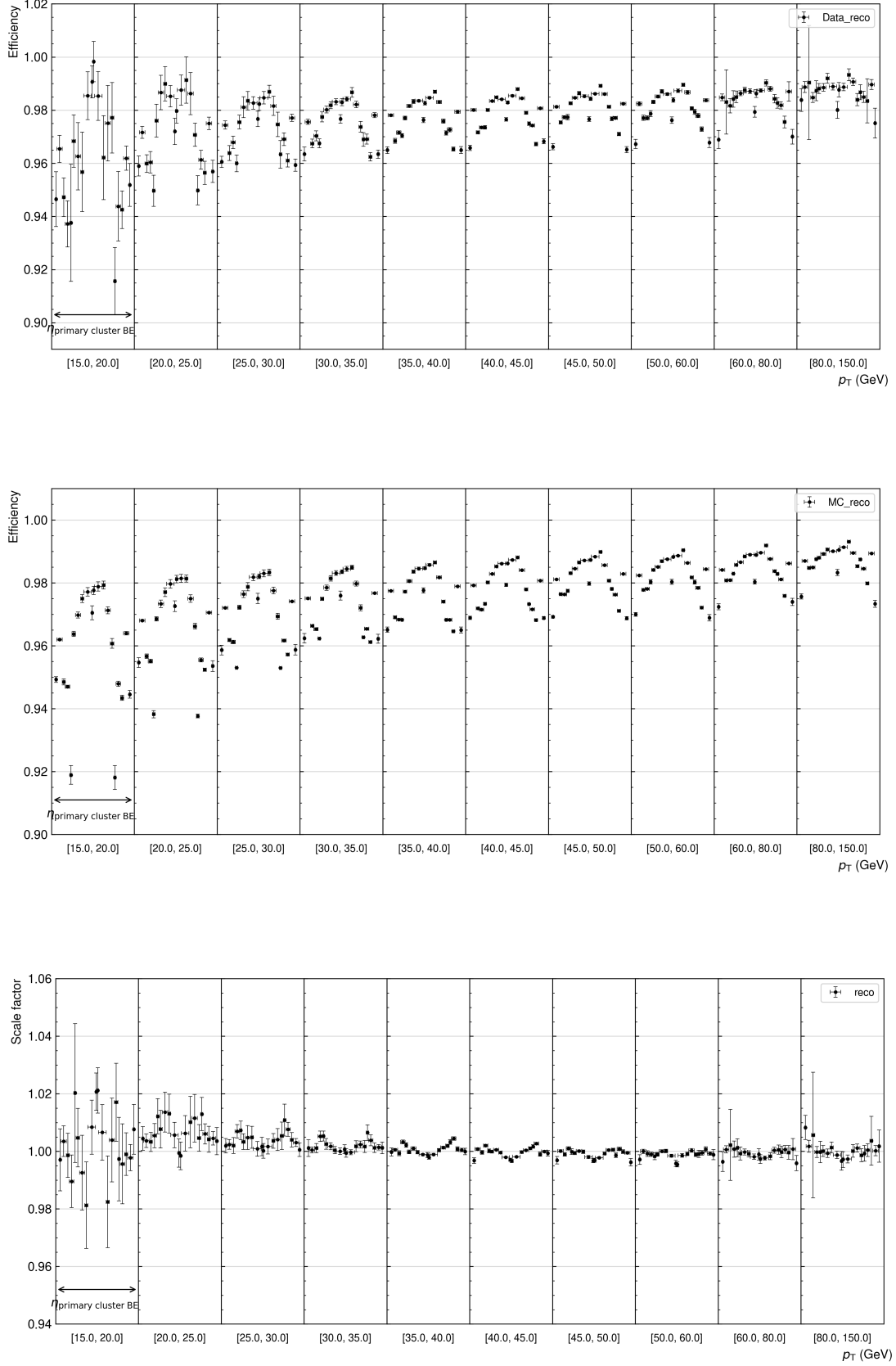


Figure 4.4: The plots for 2017 data where the first and second plot shows the data and **MC** efficiencies as a function of  $E_T$  and  $\eta$  bins (where  $\eta_{primary\ cluster\ BE2}$  refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of  $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of  $E_T$  and  $\eta$ .

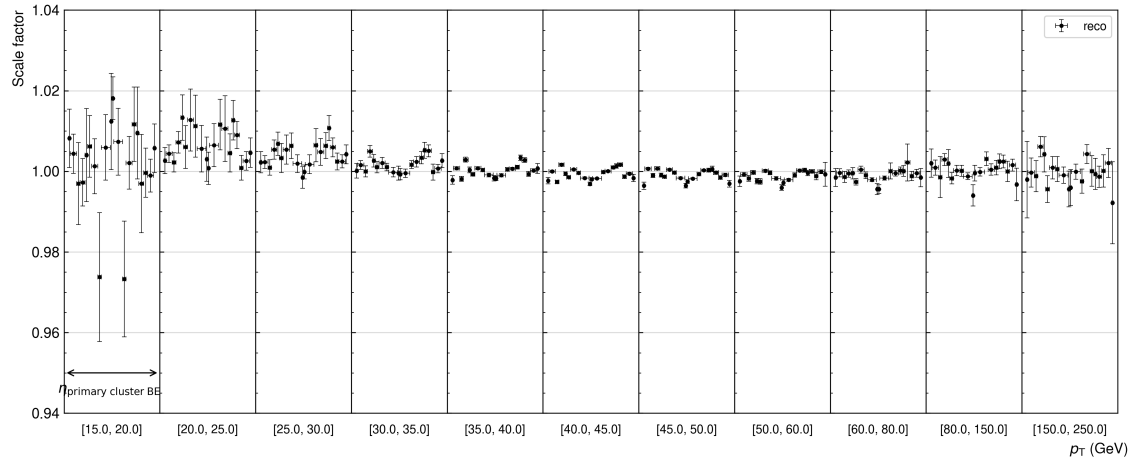
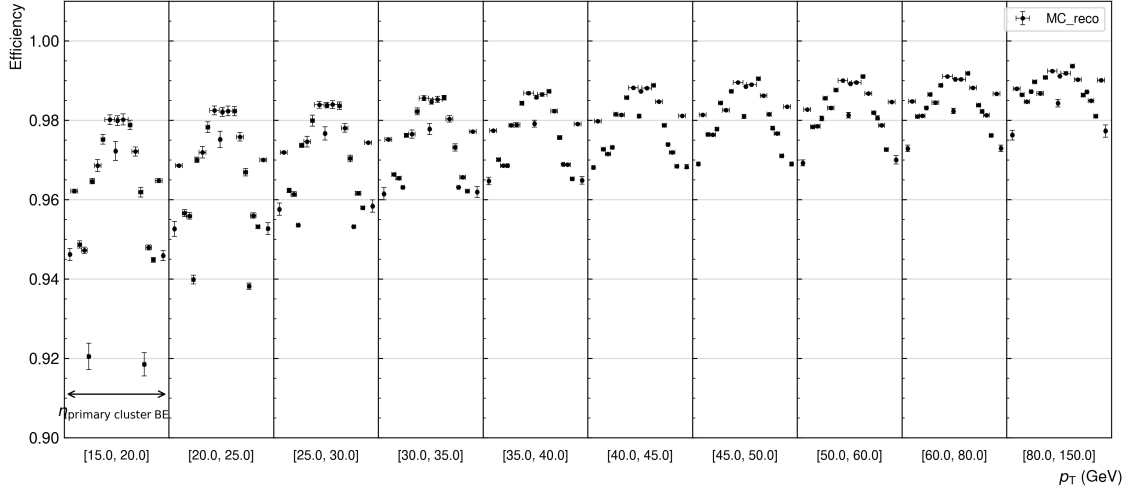
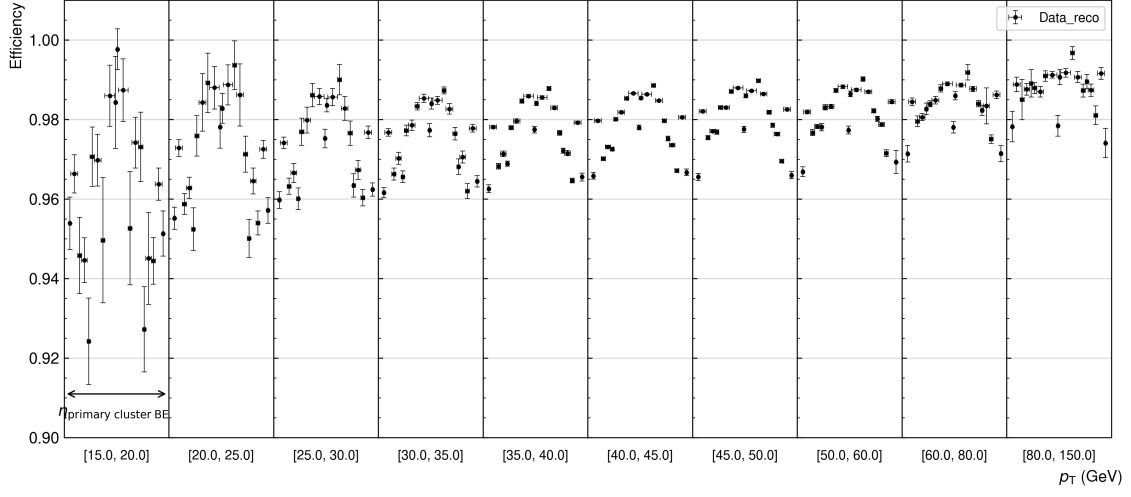


Figure 4.5: The plots for 2018 data where the first and second plot shows the data and MC efficiencies as a function of  $E_T$  and  $\eta$  bins (where  $\eta_{primary\ cluster\ BE2}$  refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of  $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of  $E_T$  and  $\eta$ .

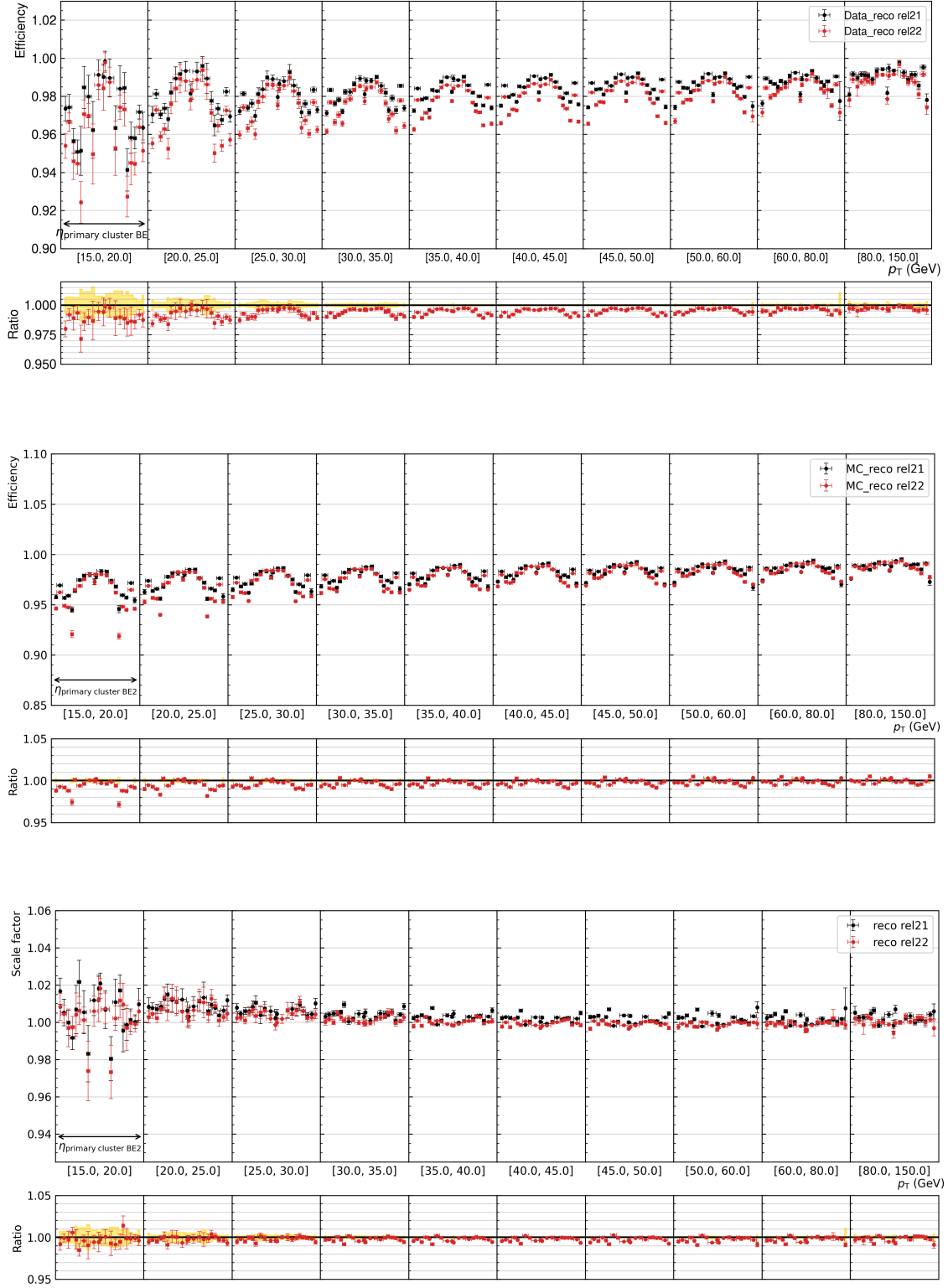


Figure 4.6: The first and second plot shows the overview of the comparison of data and mc efficiencies between rel21 and rel22 as a function of  $E_T$  and  $\eta$  for  $15 < E_T < 150\text{GeV}$  respectively while the third plot shows the same trend of scale factors all bins of  $E_T$  and  $\eta$ .

### 4.3.2 Efficiency and Scale Factors measurements with ATLAS early Run 3 data and corresponding MC samples

The efficiency measurements were performed for early Run3 data in **TagAndProbe** framework with the same scenario as explained in section 4.3.1. The datasets used to make these measurements are shown in Table A.3, where various runs are used in the Data Samples, with some runs missing. These datasets contain the Good Run List<sup>6</sup> for the proton-proton collision data taken in 2022, period E, F1, and F2 (excluding low-mu period E2), and the corresponding integrated luminosity is  $3.391 \text{ fb}^{-1}$ . The efficiencies in low  $E_T$  bins, i.e.  $15 < E_T < 20 \text{ GeV}$  and high  $E_T$  bins, i.e.  $80 < E_T < 150 \text{ GeV}$  are shown in Figure 4.7 where we can see high trends in efficiency with an increase of  $E_T$  and the bottom panels show the scale factors in the corresponding bins which look closer to unity. The total uncertainties of the efficiency are dominated by statistical ones in the data and systematic ones in the **MC** simulation, while statistical ones dominate the total uncertainties of the scale factors. In figure 4.8, the first two

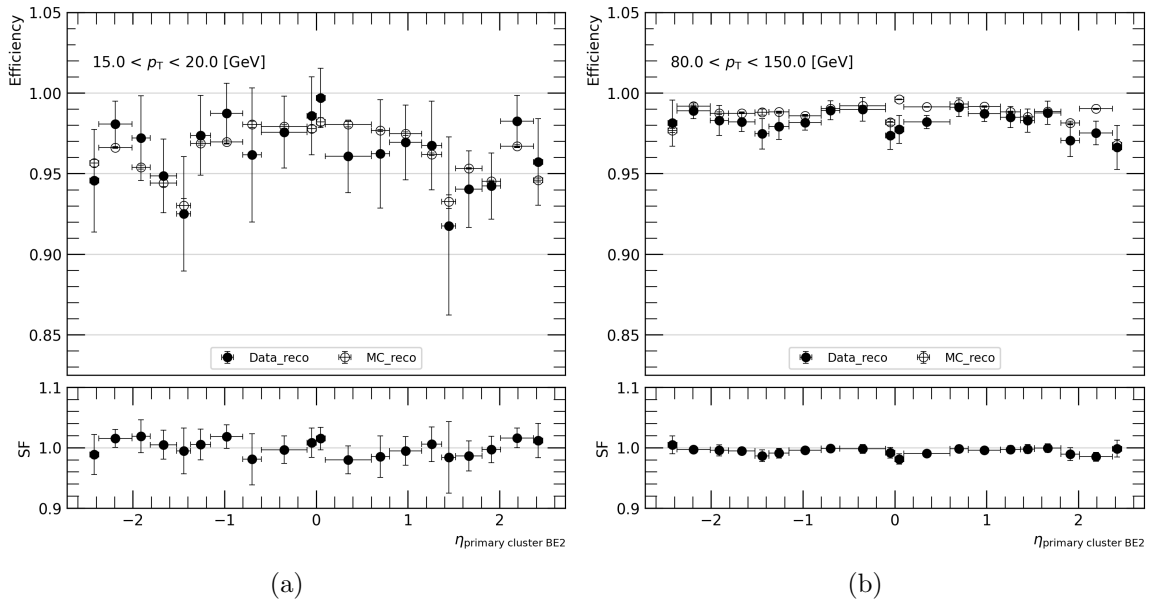


Figure 4.7: The plots a(b) for early Run 3 data depict the comparison between data efficiency and MC efficiency in the low  $E_T$  range,  $15 < E_T < 20 \text{ GeV}$ , and the high  $E_T$  range,  $80 < E_T < 150 \text{ GeV}$ . The bottom panel shows the **Scale Factors** for the corresponding bins. Error bars indicate the total uncertainties, including statistical and systematic components.

plots show the overall behaviour of data and **MC** efficiencies, respectively, as a function of  $E_T$  and  $\eta$  bins, while the third plot shows the same trend of scale factors all bins of  $E_T$  and  $\eta$ . It can

<sup>6</sup>In ATLAS analyses, a good run list is used to identify periods of data taking that meet specific quality criteria. This list includes runs where the detector was operating optimally, and various quality checks have confirmed the reliability of the data. The good run list ensures that only high-quality data, free from significant detector malfunctions or operational issues, are used in the analysis [115].

be seen that the efficiencies vary from 0.92 % to 0.99% in lower  $E_T$  bins, i.e.  $15 < E_T < 20$  GeV but higher efficiencies in higher bins range around 94% to 98% in data. In **MC**, we have less efficiency in low  $E_T$  but higher in other bins. For more of the bins, the total uncertainties of the efficiency are dominated by statistical ones in the data. The third plot shows the electron reconstruction scale factors for early run3 data, which seem to be in unity in almost all of the bins.

Figure 4.9 shows the comparison of efficiency and scale factors for early run3 and reprocessed run2 for the year 2018, i.e. results in figure 4.8 with results in figure 4.5. The run2 results are in black, while the run3 are in red. We can see that we have almost good agreement overall except in low  $E_T$  bins for all data and **MC** efficiencies and scale factors shown in the third plot.

Finally, we compare early run3 scale factors with run3\_recommendations ones in figure 4.10. The run3\_recommendations scale factors are based on Data 2018 (**rel22**) and mc20e. Scale factors are set to 1 with conservative uncertainties using Run2 recommendations, i.e.

$$SF = 1 \pm (\sigma_{Run2} \oplus |1 - SF_{Run2}|) \quad (4.9)$$

We can see that the same trend is followed as was expected. In almost all bins, the ratio lies in the yellow region, which means results oscillate around the pre-recommendations. Overall, all results have larger statistical uncertainties in the low  $E_T$  bins.

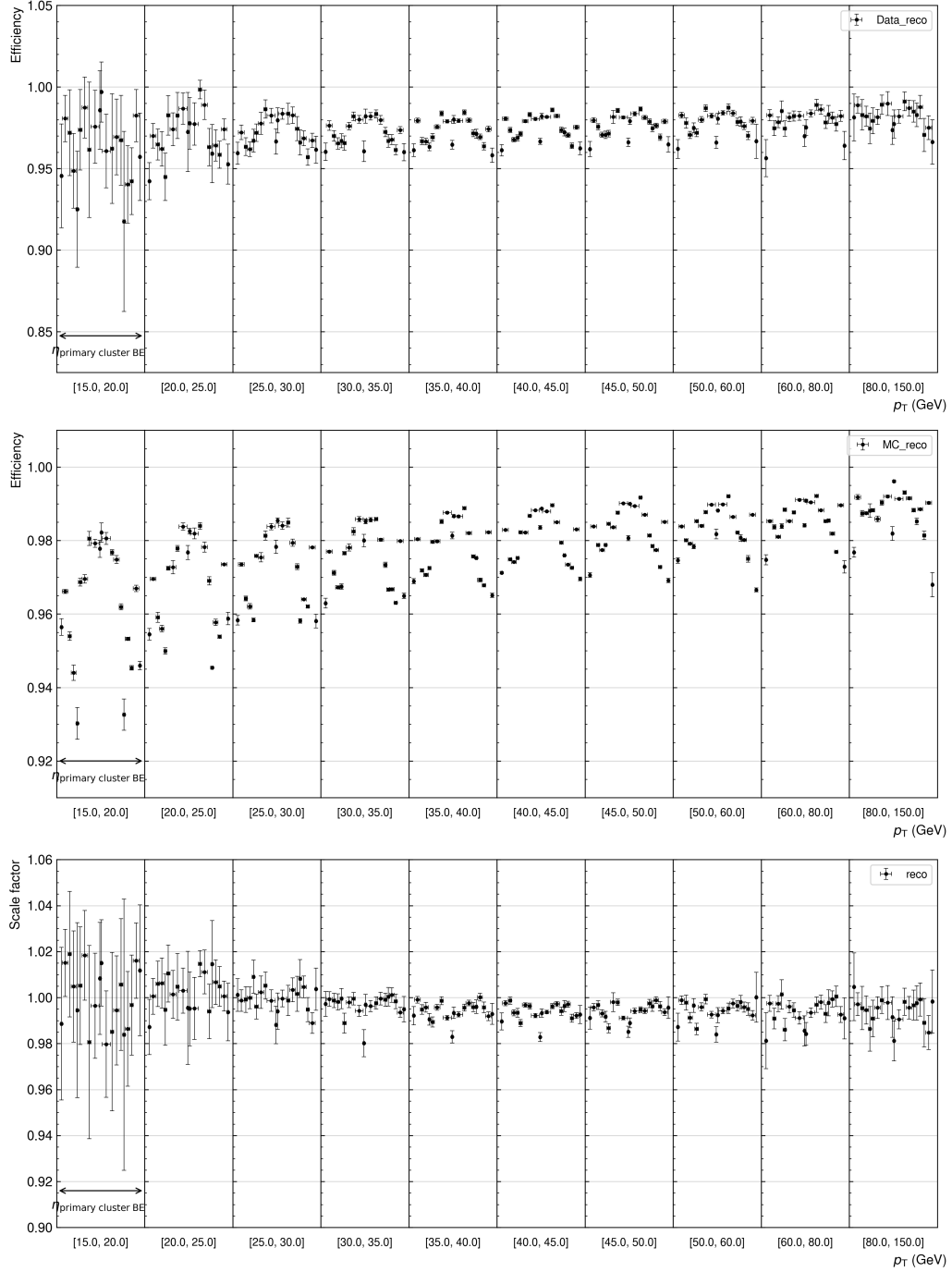


Figure 4.8: The plots for early run3 data where the first two plots show the overview of the data and MC efficiencies as a function of  $E_T$  and  $\eta$  bins (where  $\eta_{\text{primary cluster BE2}}$  refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of  $\eta$ ), respectively, while the third plot shows the same trend of scale factors all bins of  $E_T$  and  $\eta$ .



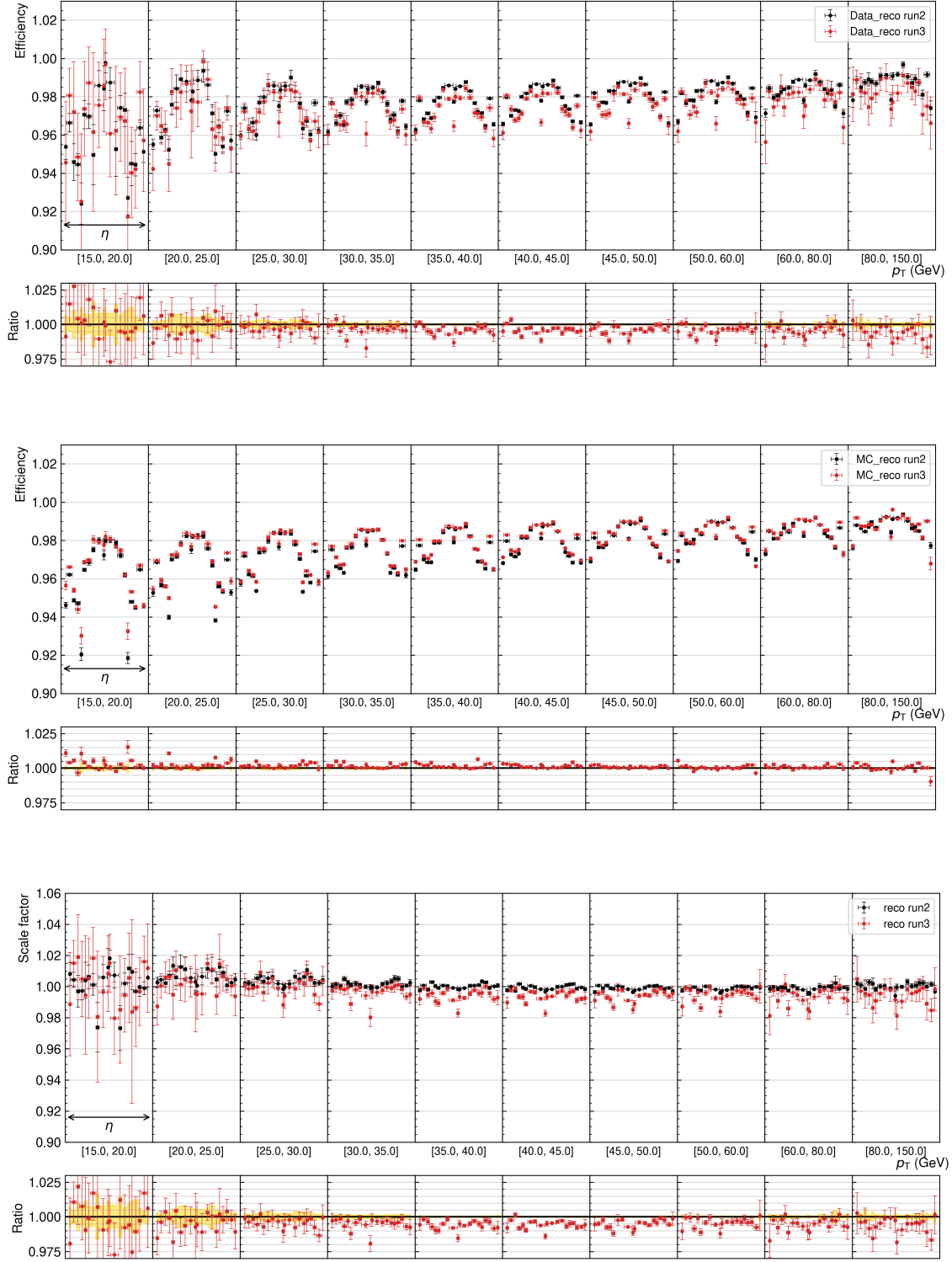


Figure 4.9: The plots make a comparison for early run3 data with data from 2018 where the first and second plot shows the overview comparison of the data and MC efficiencies as a function of  $E_T$  and  $\eta$  bins, respectively while the third plot shows the same trend of scale factors all bins of  $E_T$  and  $\eta$ .

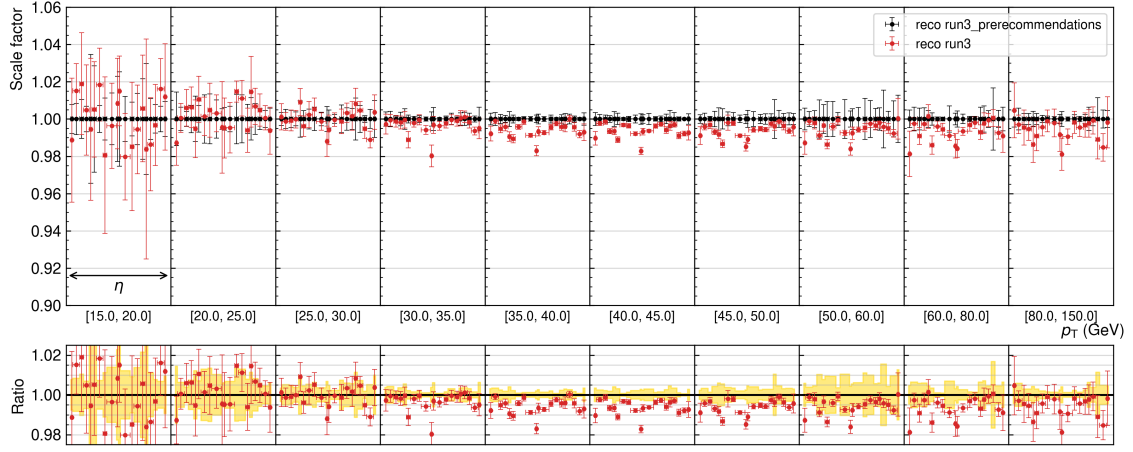


Figure 4.10: The plots compare the scale factors for early run3 data with run3 pre-recommendations as a function of  $E_T$  and  $\eta$  bins.

The main change to note for the measurement with **rel22**, whether for reprocessed Run 2 data or early Run 3 data, is the adjustment in the track-quality selection criteria, as explained in section 4.2.2. Specifically, the track-quality cut now requires  $\geq 7$  silicon hits, rather than the previous requirement of  $\geq 8$  silicon hits. All of the results discussed above are based on this updated selection criterion, where the cut is set at  $\geq 7$  silicon hits.

In contrast, a comparison plot between hits is made for early run3 **MC** efficiencies as shown in figure 4.11 where the efficiencies don't change much when switching to 8 hits. The **mc21!** (**mc21!**) samples are used to make these comparisons as given in Table A.2.

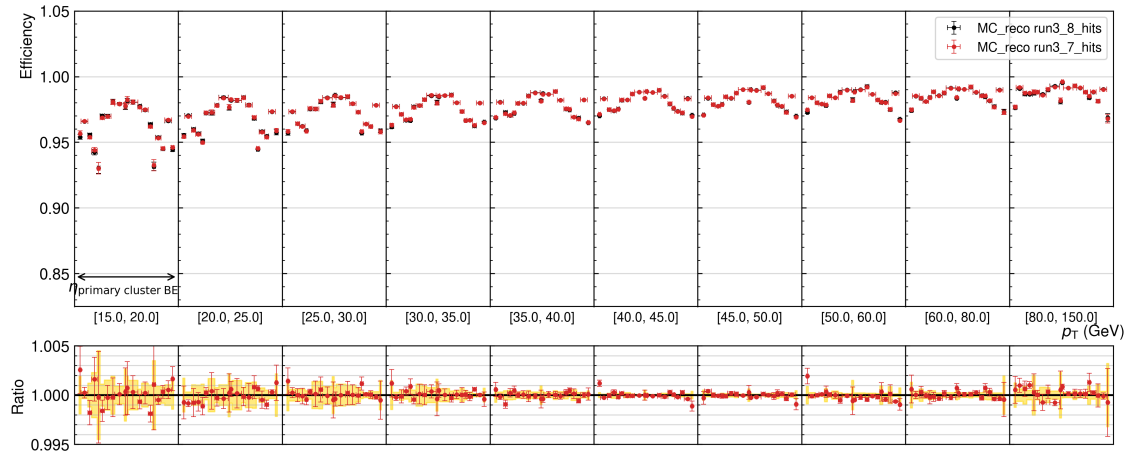


Figure 4.11: The plots compare the MC efficiencies for early run3 with silicon hits  $\geq 7$  and silicon hits  $\geq 8$  as a function of  $E_T$  and  $\eta$  bins where  $\eta_{primary\ cluster\ BE2}$  refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of  $\eta$ .

## 4.4 Summary

---

The electron reconstruction efficiency measurement methodology is briefly explained in section 4.2.3. The results of electron reconstruction efficiency and scale factors measured with full run2 reprocessed data are shown in section 4.3.1, which also explains the steps to calculate efficiency in the TagAndProbe framework. The comparison between **rel21** and **rel22** was precisely explained and shown in section 4.3.1. Finally, the results produced with early run3 data are shown in section 4.3.2, and the scale factors were compared with pre-recommendations. All efficiencies and scale factors results are taken for central values, and total uncertainties (statistical and systematic) are also shown. All comparisons are validated except for a few discrepancies in the low  $E_T$  bin in the transition region.

The results in this chapter are detailed in **ATLAS** internal note Ref. [\[107\]](#), for which I am the only author. My work focused on applying the established measurement methodology for electron reconstruction efficiency within the new Tag and Probe framework for Run 3 measurements. I also performed measurements of these efficiencies using both reprocessed Run 2 data and initial Run 3 data, as outlined in section 4.3. Additionally, I contributed to developing common software essential for measuring other electron efficiencies, such as identification, with 72 commits made to the Tag and Probe Git repository [\[116\]](#).

# Chapter 5

## Fake track studies in dense environments

### Contents

---

|            |                                                                                                 |           |
|------------|-------------------------------------------------------------------------------------------------|-----------|
| <b>5.1</b> | <b>Context and Motivation</b> . . . . .                                                         | <b>78</b> |
| <b>5.2</b> | <b>Fake Track Origins according to Monte Carlo Simulations</b> . . . . .                        | <b>79</b> |
| <b>5.3</b> | <b>Methodology for Measuring Fake Track Fractions in Jet Cores</b> . .                          | <b>81</b> |
| 5.3.1      | Event and Object Selection . . . . .                                                            | 83        |
| 5.3.2      | The Control Region Method . . . . .                                                             | 85        |
| <b>5.4</b> | <b>Discussion on results</b> . . . . .                                                          | <b>94</b> |
| 5.4.1      | Fraction of fake tracks using reprocessed Run2 Data and correspond-<br>ing MC Samples . . . . . | 94        |
| 5.4.2      | Systematic Uncertainties . . . . .                                                              | 97        |
| <b>5.5</b> | <b>Summary</b> . . . . .                                                                        | <b>99</b> |

---

In this chapter, I will present my own results. For the general description, I used the following bibliographic sources:

- ATLAS Collaboration, “Early Inner Detector Tracking Performance in the 2015 data at  $\sqrt{s} = 13$  TeV” [117]
- ATLAS Collaboration, “Modelling of Track Reconstruction Inside Jets with the 2016 ATLAS  $\sqrt{s} = 13$  TeV pp dataset” [118]

This chapter discusses the research conducted to evaluate the accuracy of **Fake Tracks (FT)** modelling within the core of the **ATLAS ID**. This study was conducted with a combined effort of the **ATLAS** Clustering and Tracking in dense environment (CTIDE) group. **My own results presented in this chapter are contained in an ATLAS internal note in Ref. [119] where I am one of the 3 authors with the role of a main analyser.**

## 5.1 Context and Motivation

---

Reconstructing the tracks and measuring their parameters accurately is essential for most high-energy physics research. For instance, finding displaced vertices and unusual track patterns can be important clues for discovering new particles [120]. While reconstructing isolated tracks, such as those from leptons in leptonic Z-decays, is relatively straightforward, more challenging situations arise in the dense core of high transverse momentum jets due to the high particle density, as displayed in Figure 5.1 and also as illustrated in 5.2b, where we can see that, this high particle density can result in more than 100 tracks per jet. When many charged particles pass through this region, they leave signals on the pixel detectors in the **ATLAS ID**. Normally, each particle produces a distinct cluster of signals on the detector, allowing us to track individual particles. However, these clusters begin to overlap or merge at high particle densities, making it difficult to distinguish the signals from separate particles. This merging complicates the identification of individual particle trajectories. As a result, some tracks might be incorrectly reconstructed, a phenomenon referred to as fake tracks. These tracks do not correspond to the actual paths of particles produced in collisions but instead arise due to imperfections in the detector and data processing algorithms. If **FT** are poorly modelled, they can lead to inaccurate particle identification and reconstruction. This misidentification can affect the accuracy of particle momentum and energy measurements. Additionally, the presence of **FT** can increase background noise and reduce the sensitivity of searches for new physics. On the other hand, the “real tracks” represent the genuine paths traced by actual particles as they traverse the detector. These tracks provide reliable data on particle properties, such as momentum and energy. Real tracks originate from the collision or interaction point of interest and serve as dependable data points.

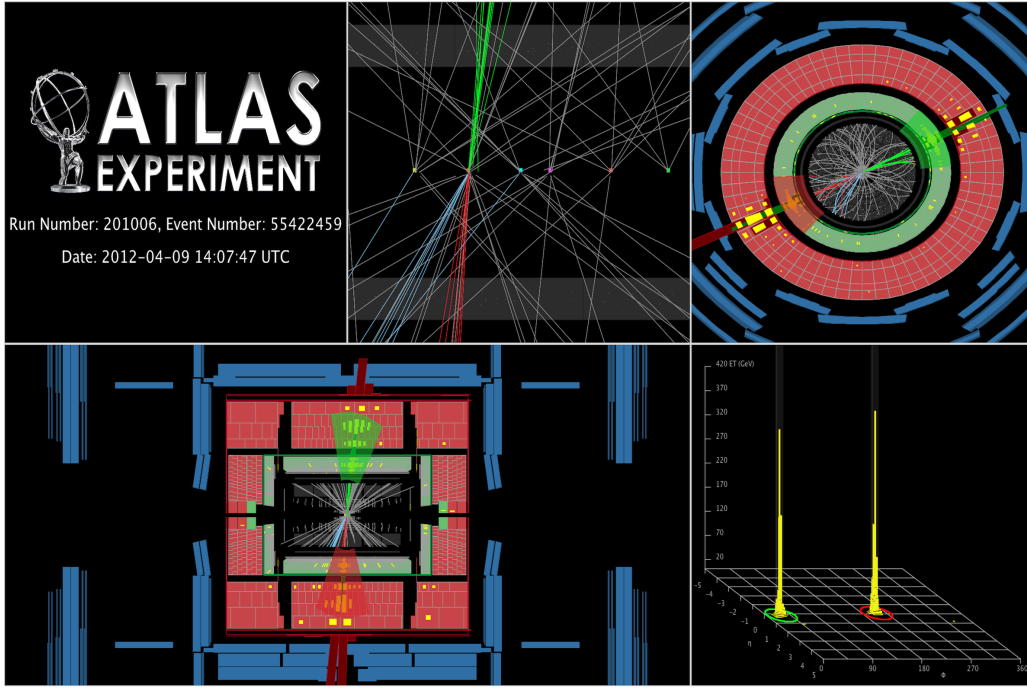


Figure 5.1: Graphical representation of a proton-proton collision featuring a high-mass dijet event captured during LHC Run 1 in 2010 [121].

This chapter presents the measurements of the rate of **FT** inside the core of jets. These measurements are done using data recorded within the **ATLAS** detector from 2015 to 2018 at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV. Initially, to understand the origin of **FT** are presented in Section 5.2. Secondly, the method used to measure the fraction of **FT** in the core of the jet is described in Section 5.3, as well as the results and the final uncertainties in Section 5.4.

## 5.2 Fake Track Origins according to Monte Carlo Simulations

In the context of the **ATLAS** detector, **FT** are often comes from the random combination of hits. However, in the dense environments at the core of high transverse momentum jets, the rate of **FT** can increase significantly. This increase is not only due to higher particle density but also because the detector is more crowded with signals from multiple particles passing through the same region. As a result, the reconstruction algorithms can mistakenly combine hits from different particles into a single track. Additionally, high pileup conditions, where multiple interactions occur in the same event, further contribute to the increase in **FT**.

Figure 5.2 (a) shows that the rate of **FT** increases from 0.1% to almost 0.2% as  $\langle\mu\rangle$  rises from 5 to 80, with a  $\Delta R(\text{jet}, \text{track}) < 0.2$ . A similar trend is seen when tightening the  $\Delta R(\text{jet}, \text{track})$  selection.

In Figure 5.2 (b), the **FT** rate goes from 0.1% up to 0.7% when looking at its distribution versus the number of tracks forming the jet, with a  $\Delta R(\text{track}, \text{jet}) < 0.2$  selection. When the selection is tightened to  $\Delta R(\text{track}, \text{jet}) < 0.1$ , the **FT** rate increases further to 0.9%, indicating that close-by-track merging processes dominate in this region.

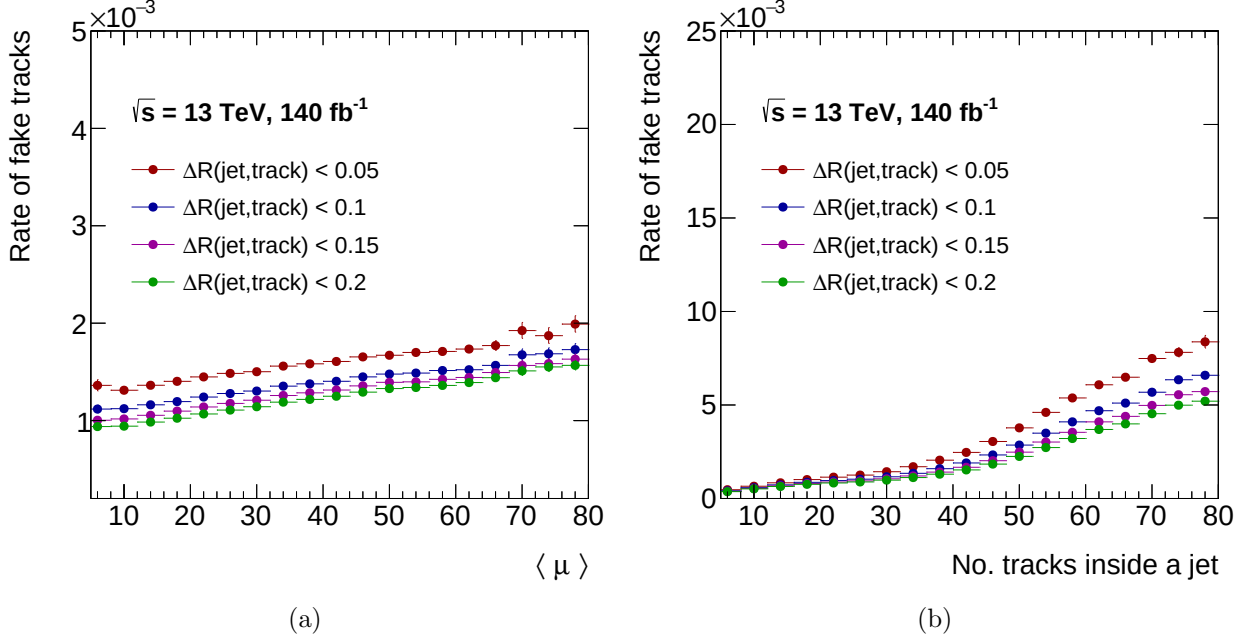


Figure 5.2: (a) Rate of fake tracks as a function of the average number of interactions per bunch crossing  $\langle \mu \rangle$ . (b) Rate of fake tracks as a function of the number of tracks inside a jet. Distributions obtained in MC simulation for several  $\Delta R(\text{jet}, \text{tracks})$  intervals. The plots include  $\Delta R(\text{jet}, \text{track})$  thresholds of 0.05 (red), 0.1 (blue), 0.15 (purple), and 0.2 (green). Only the statistical uncertainties are shown.

In **MC** simulations, the identification of fake and real tracks is achieved by matching reconstructed tracks to the original particles (truth particles) responsible for their creation. Each hit, which represents the emulation of a recorded signal in the detector, is assigned to the particle that deposited the most energy in that location during the simulation. To establish this match, each reconstructed track is associated with the truth particle that best corresponds to it based on the track's properties and the particle's trajectory. In cases where multiple truth particles could be associated with a single reconstructed track, the match is determined by the particle most accurately aligns with the track's kinematic and spatial characteristics. Hits are then grouped into clusters, and each hit is weighted according to its impact on the track reconstruction. The weight reflects how significantly the position of the hit in a particular detector layer influences the overall track fit, ensuring that the most relevant hits contribute most to the track's reconstruction accuracy. Hits from different parts of the detector (**PIXEL**, **SCT**, **TRT** (introduced in section 3.4)) get different weights:

- Pixel detector (including **IBL**): Weight = 10
- **SCT**: Weight = 5
- **TRT**: Weight = 1

We calculate a matching probability called **truth-reco track matching probability**,  $P_{\text{match}}$ , by comparing the number of hits that both a reconstructed track and the original particle share ( $N^{\text{common}}$ ) to the total number of hits in the track ( $N^{\text{track}}$ ). The formula looks like this:

$$P_{\text{match}} = \frac{10 \times N_{\text{Pixel}}^{\text{common}} + 5 \times N_{\text{SCT}}^{\text{common}} + 1 \times N_{\text{TRT}}^{\text{common}}}{10 \times N_{\text{Pixel}}^{\text{track}} + 5 \times N_{\text{SCT}}^{\text{track}} + 1 \times N_{\text{TRT}}^{\text{track}}}$$

To classify the fake and real tracks, if  $P_{\text{match}}$  is over 50%, we say the track is real. If it's less, the track is fake. Real tracks have parameters (like momentum and impact parameters) that match well with the original particle's path within the expected uncertainties (determined by the track fitting procedure). On the contrary, **FT** show significant differences; for example, the distribution of quantities like the impact parameter is about three times wider than one would expect from the track fit uncertainty if the track were real.

This method is reliable because it looks at the detailed relationship between tracks and particles at the simulation's energy deposit level and is mostly independent of the detector resolutions. This helps accurately distinguish real tracks from fake ones.

## 5.3 Methodology for Measuring Fake Track Fractions in Jet Cores

---

Section 3.2 introduced the geometry of the **ATLAS** detector, and the basic parameters used for reconstructing any physics object have been explained. However, there are additional useful parameters used to describe tracks and also depicted in figure 5.3 and given as:

- $z_0$  (Longitudinal Impact parameter): The difference between the  $z$ -coordinate of the point where the extrapolated trajectory of the particle comes closest to the beam axis and the  $z$ -coordinate of the primary vertex.
- $d_0$  (Transverse Impact parameter): The distance in the  $x$ - $y$  plane from the particle's path to the beam axis.
- $\phi$  (Azimuthal Angle): The angle around the  $z$ -axis of the particle's momentum at the closest point ranges from  $-\pi$  to  $\pi$ .
- $\theta$  (Polar Angle): The angle from the  $z$ -axis to the particle's path at the closest point ranges from 0 to  $\pi$ .



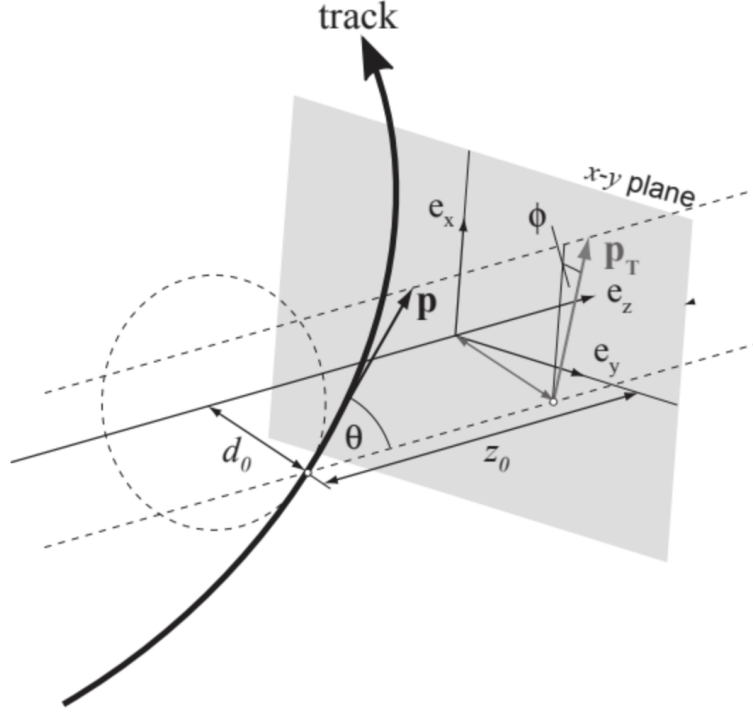


Figure 5.3: Illustration of the geometric parameters used to describe the track of a charged particle in the ATLAS detector. The particle's path is represented by a curved line, indicating its trajectory under the influence of the detector's magnetic field. The closest point on the particle's path to the beam spot position is where the particle comes nearest to it [122].

The charge-to-momentum ratio ( $q/p$ ) of the particle's charge to the magnitude of its momentum is also a key parameter in reconstructing tracks because it directly affects the curvature of the particle's trajectory in a magnetic field. This curvature is essential for determining the particle's momentum and is fundamental for accurate track reconstruction.

### 5.3.1 Event and Object Selection

To measure the fraction of **FT**, specific selection criteria are applied to both tracks and jets to ensure that the dataset is consistent regarding track quality and jet characteristics. These pre-selections help to refine the data by focusing on the most relevant events. The premise pre-selection criteria for the tracks and jets are listed below.

- **Track Selection:**

- Only those tracks originating from the primary collision vertex are considered to minimize the effect of overlapping tracks.
- Only tracks with a pseudorapidity ( $|\eta| < 2.5$ ) are chosen.
- The transverse momentum of the tracks must be greater than 1 GeV while below this threshold, the region is dominated by real tracks.
- Tracks are further filtered to include only those within the leading jet by requiring a minimum distance ( $\Delta R$ ) of 0.2 between the leading jet and the track<sup>1</sup>.

- **Jet Selection:**

- The jets are reconstructed from **P-flow** clusters using the anti- $k_t$  algorithm with four-momentum recombination and distance parameter  $R = 0.4$ . **P-flow** clustering involves gathering information from calorimeters to reconstruct jets (more information can be found in section 3.5.4).
- At least two signal jets with  $p_T > 150$  GeV must be present in the event<sup>2</sup>.
- The leading jet must be central, with  $|\eta| < 2.5$ .
- The transverse momentum of the leading jet must be between 470 and 600 GeV. This range<sup>3</sup> ensures that the same type of di-jet events are selected in both data and MC simulations<sup>4</sup>.

To ensure high-quality track selection, specific criteria are applied to the tracks. In general, two types of track selection operating points are used to improve the quality of the selected track. One has loose track selection and is called **LooseWP**, and the second is based on the strictness of the criteria and called **TightPrimaryWP** specified in Ref. [117] and defined in Ref. [123]. The nominal measurement is performed using the **LooseWP** for the track selection while results with

---

<sup>1</sup>The requirements like 0.15, 0.1 or 0.05 are used as a cross-check, or to assign the final systematic uncertainty.

<sup>2</sup>We aim to use a simulation sample representative of the actual data, focusing specifically on **QCD** dijet production. For the simulation to be valid, the event must contain at least two signal jets.

<sup>3</sup>There are two types of MC samples used in this analysis, filtered by jet transverse momentum ( $p_T$ ). For the **Loose** operating point, we use JZ4 samples merged with JZ5 samples, which are combined based on the jets' specific  $p_T$  ranges. If only JZ5 samples are requested, the condition is set to  $490 < p_T < 600$  GeV. Additionally, results for the **TightPrimaryWP** are available only for JZ4 samples and are presented in Appendix B.

<sup>4</sup>The MC sample is a di-jet sample filtered to have a jet  $p_T$  between 400 and 1300 GeV.

TightPrimaryWP are given in appendix B.

## Loose Track Selection Criteria (LooseWP)

- **Silicon Hits:** A track must have at least 8 silicon hits (pixel + **SCT**).
- **Pixel Holes**<sup>5</sup>: A track can have a maximum of 1 hole in the pixel detector.
- **Silicon Holes:** A track can have a maximum of 2 holes in the silicon detector.
- **Shared Modules:** A track can have a maximum of 1 shared module (1 shared pixel hit or 2 shared **SCT** hits)<sup>6</sup>.

## Tight Primary Track Selection Criteria (TightPrimaryWP)

- **Silicon Hits:** For  $|\eta| \leq 1.65$ , a track must have at least 9 silicon hits. For  $|\eta| > 1.65$ , it must have at least 11 silicon hits.
- **IBL and B-Layer Hits:** A track must have a hit in either the **IBL** or B-layer (if hits in both are expected).
- **Innermost Pixel Layers:** A track must have at least 1 hit from both innermost pixel layers (if a hit is expected but not present, it is counted as 1).
- **Pixel Holes:** A track must have no holes in the pixel detector.
- **Silicon Holes:** A track can have a maximum of 2 holes in the silicon detectors.
- **Shared Modules:** A track can have a maximum of 1 shared module (1 shared pixel hit or 2 shared **SCT** hits).

The LooseWP uses less strict selection criteria, allowing for higher track reconstruction efficiency, which is crucial when capturing a larger sample of potential tracks. In contrast, the TightPrimaryWP uses stricter criteria to filter out low-quality or **FT** more effectively, leading to a lower fraction of **FT** but slightly reduced efficiency for real track reconstruction. This distinction is reflected in Table 5.1, where the LooseWP shows higher overall efficiency, particularly for tracks with  $P_T > 2$  GeV. In contrast, the TightPrimaryWP significantly reduces the fake track fraction.

The table 5.1 summarises the performance numbers for both track selection criteria under  $\langle \mu \rangle = 40$  pile-up conditions. It is evident that while LooseWP achieves a higher reconstruction efficiency (84.60% for all tracks, 87.12% for tracks with  $P_T > 2$  GeV), this comes at the cost of a higher fake track fraction (14.43% for all tracks, 7.79% for  $P_T > 2$  GeV). On the other hand,

---

<sup>5</sup>A “hole” refers to a missing but expected measurement point along a track’s trajectory. If the track crosses an inactive module, it is not considered a hole [124].

<sup>6</sup>Shared Hit: A hit is considered as shared if it is used by more than one reconstructed track [124].

**TightPrimaryWP** sacrifices some efficiency (77.38% for all tracks, 82.11% for  $P_T > 2$  GeV) in exchange for a much lower fake track fraction (3.67% for all tracks, 1.13% for  $P_T > 2$  GeV).

Additionally, it's important to note the regional differences in performance, particularly in the pseudorapidity range  $2.3 \leq |\eta| \leq 2.5$ , where efficiency drops by 20% compared to the  $|\eta| < 0.1$  region. This variation illustrates how both operating points face challenges in high- $|\eta|$  regions, but **TightPrimaryWP** remains more selective across the entire detector acceptance range.

| Events with $t\bar{t}$ signals, where the average number of pile-up interactions is $\langle\mu\rangle = 40$ . |            |               |               |               |
|----------------------------------------------------------------------------------------------------------------|------------|---------------|---------------|---------------|
|                                                                                                                | Efficiency |               | Fake fraction |               |
|                                                                                                                | All tracks | $p_T > 2$ GeV | All tracks    | $p_T > 2$ GeV |
| LooseWP                                                                                                        | 84.60%     | 87.12%        | 14.43%        | 7.79%         |
| TightPrimaryWP                                                                                                 | 77.38%     | 82.11%        | 3.67%         | 1.13%         |

Table 5.1: Efficiency and Fake Track Fraction for **LooseWP** and **TightPrimaryWP** working points, based on MC simulation with an average pile-up of  $\langle\mu\rangle = 40$  in  $t\bar{t}$  events [124].

Figures 5.4 through 5.8 illustrate the distributions of several key variables after pre-selection for **LooseWP**. These key variables include the leading and sub-leading jet  $\eta$  and  $p_T$ , the number of jets, the number of tracks forming a jet, the number of pixel hits and pixel holes, the number of **SCT** hits, **SCT** holes, **SCT** shared hits, the combined number of **TRT** outliers<sup>7</sup> and **TRT** hits, and the track  $\chi^2/n_{\text{DOF}}$ <sup>8</sup>. Generally, the data and the **MC** simulation are observed in good agreement across all distributions obtained directly after the pre-selection. This consistency between data and simulation indicates that the pre-selection criteria are effective and that the **MC** simulation accurately models the actual data. In some of these Figures, the **MC** simulation is plotted separately for fake and real tracks, demonstrating the discrimination power of the selected variables.

### 5.3.2 The Control Region Method

To estimate the rate of **FT** in real data, we conduct a fit in a **Control Region (CR)** enriched with **FT** (known as CR-F). To optimise this **CR**, we use **MC** simulation studies to find variables that can effectively distinguish **FT** from real ones. As a result of this optimisation, we define the CR-F using variables like Track Transverse impact parameter ( $d_0$ ),  $\sin\theta \times |z_0^{PV}|$  where  $z_0^{PV}$  is the track longitudinal impact parameter computed with respect to the primary vertex,

<sup>7</sup>TRT Outliers: Number of TRT hits nearby the track but not included in the track fit

<sup>8</sup> $\chi^2$  is a statistical measure used to compare observed data points with the values predicted by a theoretical model. Specifically, it sums the squared differences between each observed data point and the corresponding predicted value. DOF stands for degree of freedom.

Track  $\chi^2/\text{DOF}$ , number of **SCT** hits, number of Pixel hits, the sum of the number of **TRT** and **TRT** Outliers hits. All the requirements on these variables are shown in Table 5.2.

| Variables to define<br><b>CR-F</b>             | Requirement                                        |
|------------------------------------------------|----------------------------------------------------|
| Track transverse impact<br>parameter ( $d_0$ ) | Greater 0.2 mm                                     |
| $\sin \theta \times  z_0^{\text{PV}} $         | Greater 0.3 mm                                     |
| Track $\chi^2/\text{DOF}$                      | Greater 1.2                                        |
| Number of SCT hits                             | $n_{\text{SCT}} \leq 9$                            |
| Number of Pixel hits                           | $n_{\text{Pix}} > 0$                               |
| Number of TRT + TRT<br>Outliers hits           | $n_{\text{TRT}} + n_{\text{TRT Outliers}} \leq 36$ |

Table 5.2: Summary of variables and their requirements for defining the control region enriched in fake track.

A variable like track  $p_T$  effectively distinguishes between fake and real tracks. However, to ensure the results of this study remain unbiased and independent of specific physics processes, we do not use this variable to define the **CR**.

The distribution of the truth-reco track matching probability for **LooseWP** after the pre-selection and after each requirement used to define the **CR** is shown in Figure 5.11. Just after the pre-selection, the sample is clearly dominated by real tracks (black dots), while the CR-F (light blue diamonds). The obtained **CR** has the ratio between fake and real tracks around 22%. The statistics in data, as well as the (similar) selection efficiencies in data and **MC** simulation for each **CR** criterion, are shown in Table 5.3. The efficiencies in data and **MC** agree very well (maximum 7% difference).

The fractions of fake and real tracks are fitted to the data histograms in the **CR** using a standard **Maximum Likelihood Estimation (MLE)** based on Poisson statistics, as implemented in the **TFractionFitter** class within **ROOT** [125].

Figures 5.9 and 5.10 show the distributions of the variables used to define the **CR**, and they demonstrate good agreement between the data and the **MC** simulation across all distributions in the **CR**. To highlight the discriminating power of the selected variables, the **MC** distributions for the fake and real tracks are also shown in Figures 5.9 and 5.10. These findings provide assurance when utilising the **MC** distributions in the **CR** to fit the fraction of fake and real tracks.

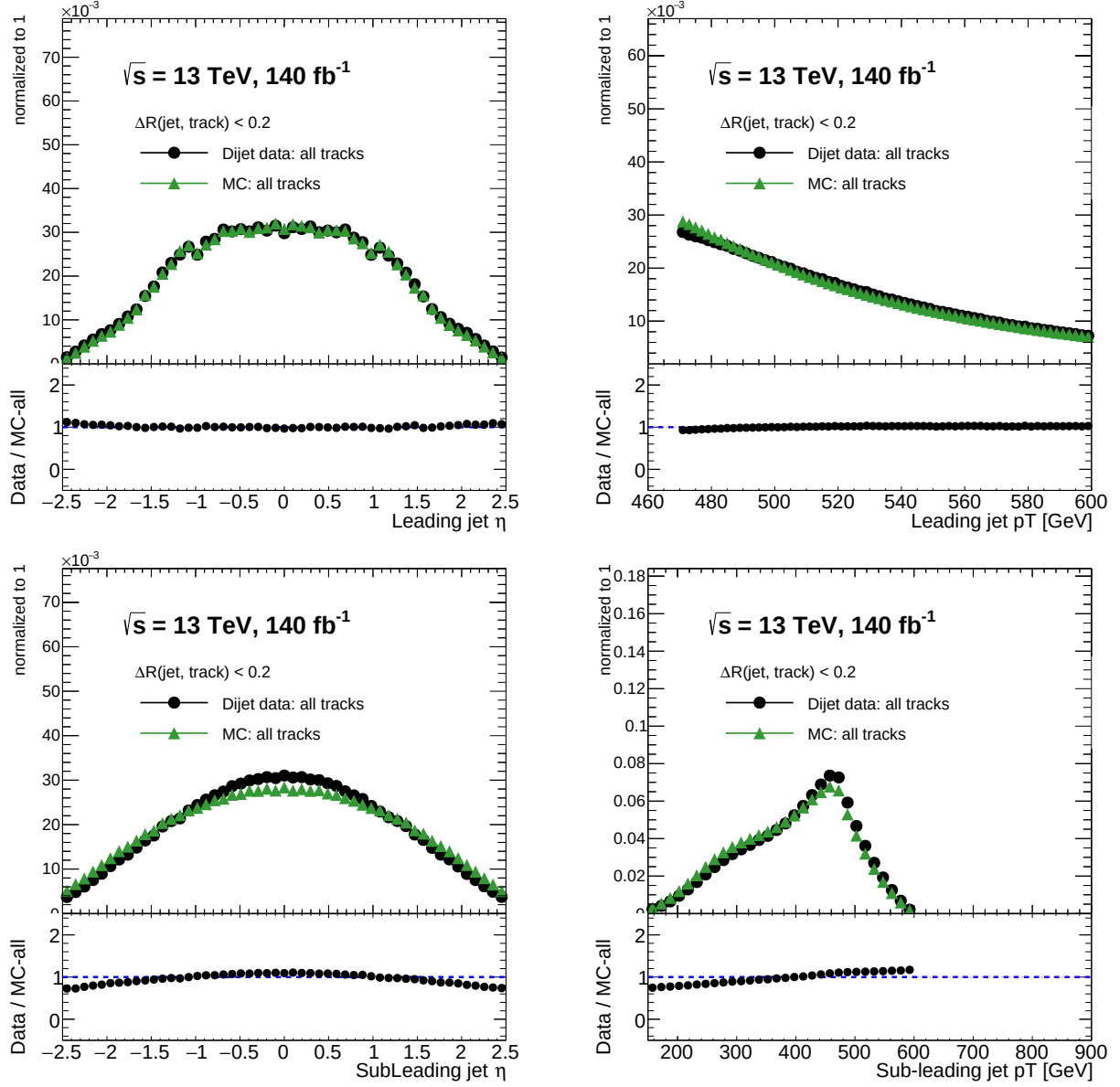


Figure 5.4: Distributions for LooseWP after the pre-selection. The top left and bottom left plots show the leading and sub-leading jet  $\eta$  distributions, respectively. The top right and bottom right plots show the leading and sub-leading jet  $p_T$  distributions, respectively. Black dots represent data points, and green up-triangles represent MC for all tracks. The ratio plots beneath each distribution compare the data to MC, with the last bin in each distribution including overflow events.

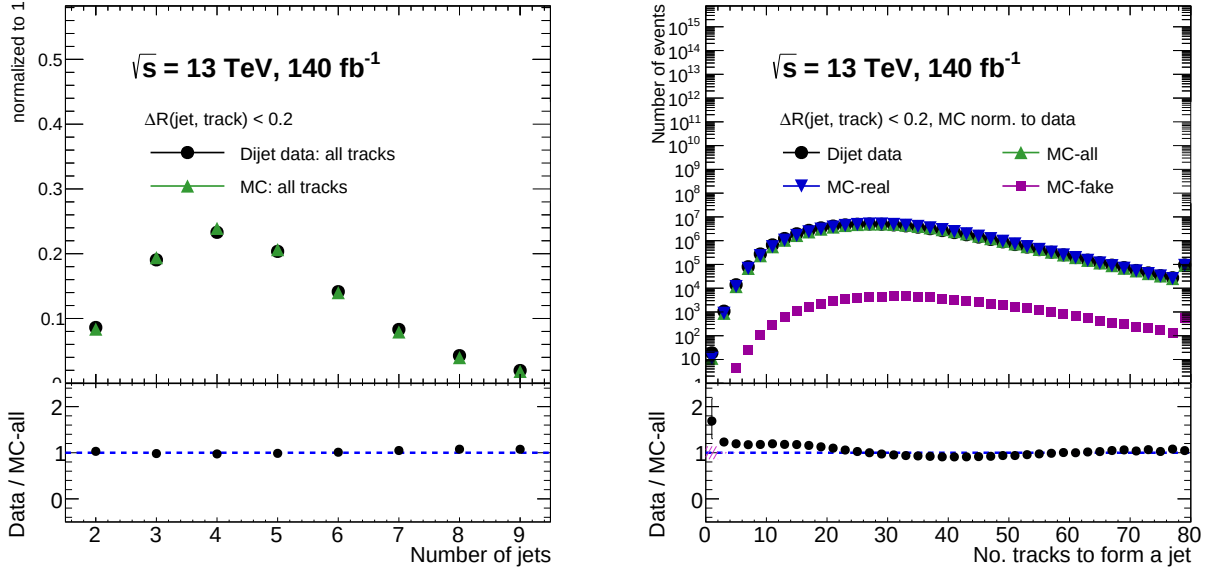


Figure 5.5: Distributions for LooseWP following the pre-selection. The plot on the left displays the number of jets, while the right plot illustrates the number of tracks in the jet. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events.

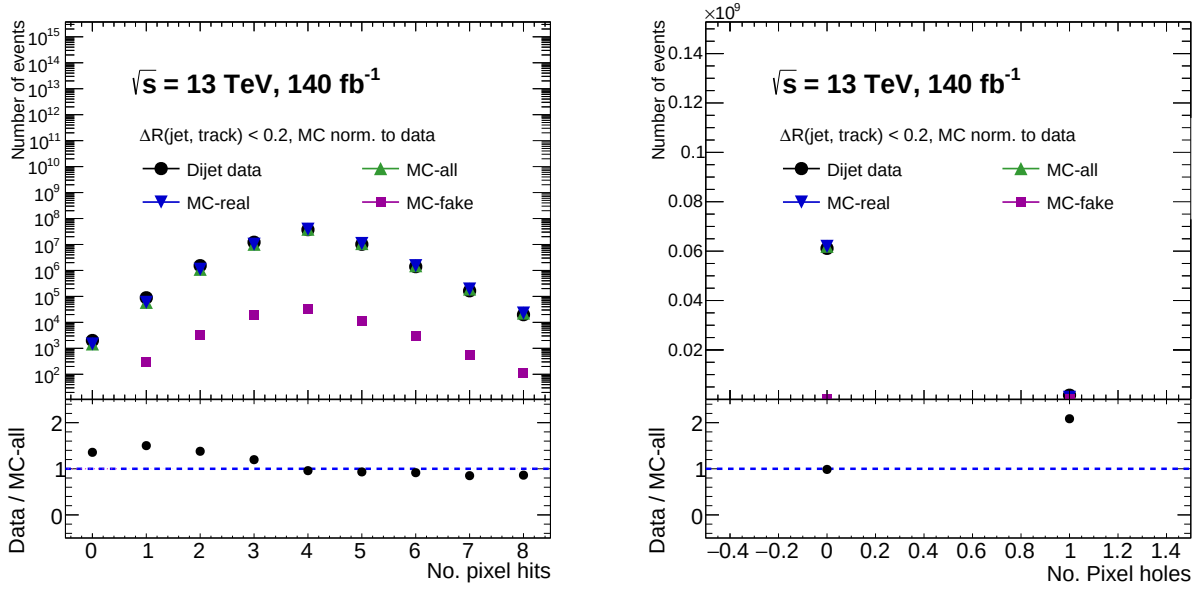


Figure 5.6: Distributions for LooseWP after the pre-selection. The left plot shows the distribution of the number of pixel hits, while the right plot shows the distribution of the number of pixel holes. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events.

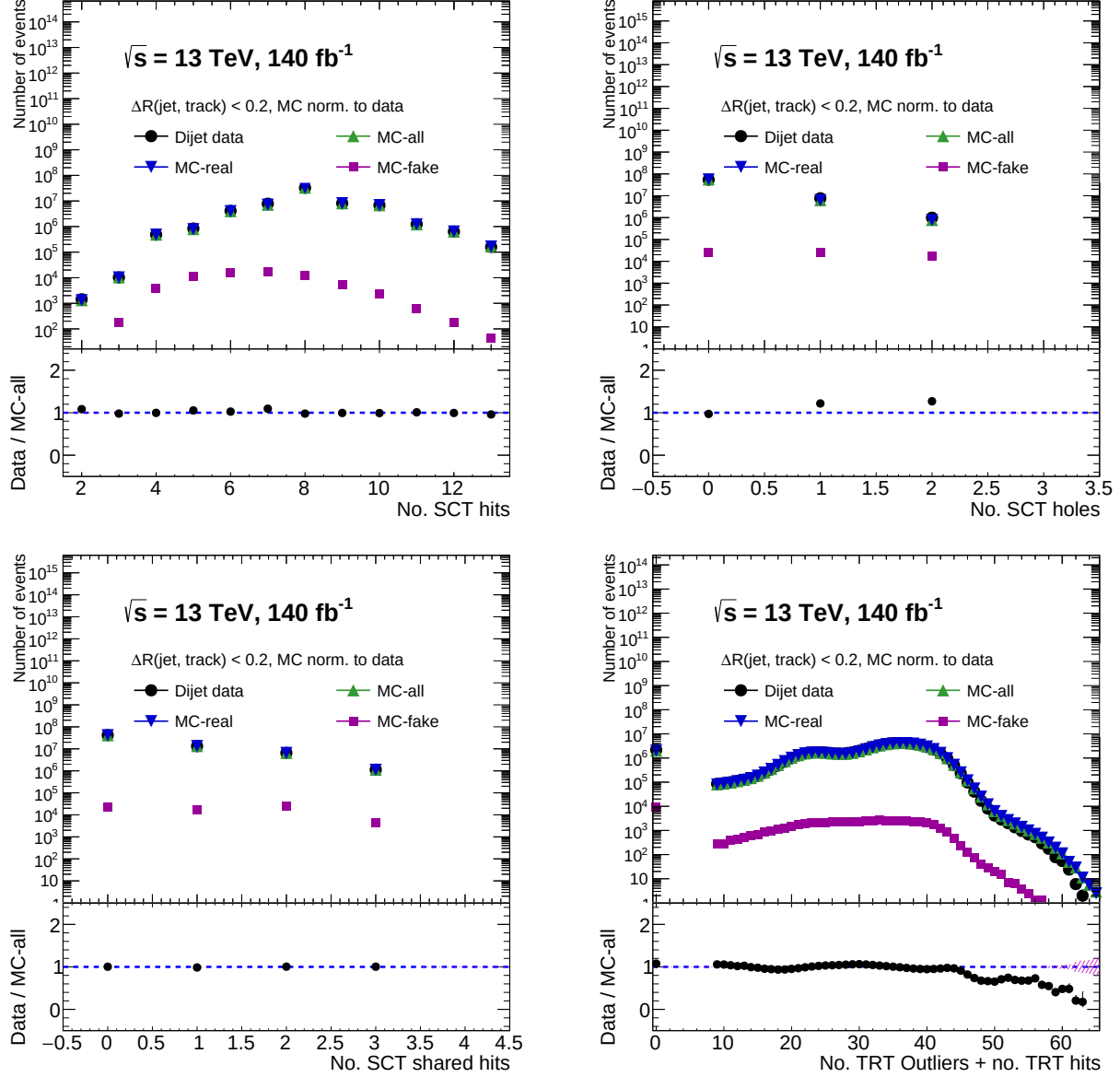


Figure 5.7: Distributions for LooseWP after the pre-selection. The top left plot shows the distribution of the number of SCT hits, the top right plot shows the distribution of the number of SCT holes, and the bottom left plot shows the distribution of the number of SCT shared hits. The bottom right plot shows the distribution of the combined number of TRT outliers and TRT hits. The results are shown for data (black dots), and MC contribution is either inclusively or split into separate real/fake track components. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in both distributions including overflow events.



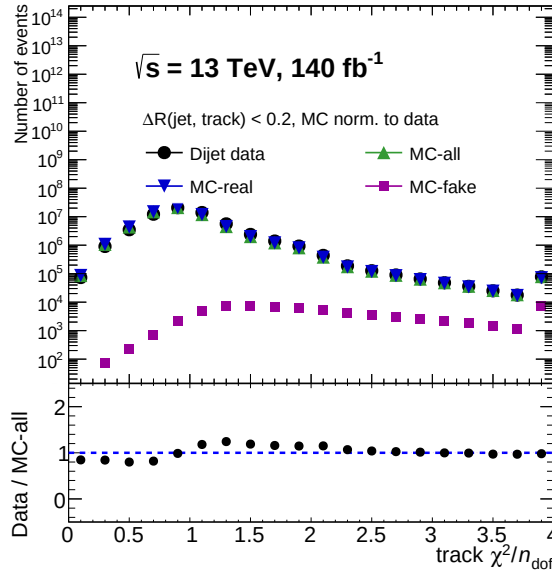


Figure 5.8: Distributions for LooseWP of the track  $\chi^2/\text{DOF}$  variable after pre-selection, shown for both data and MC simulation. The final bin accounts for overflow. The hashed magenta region in the lower panel indicates the MC statistical uncertainty.

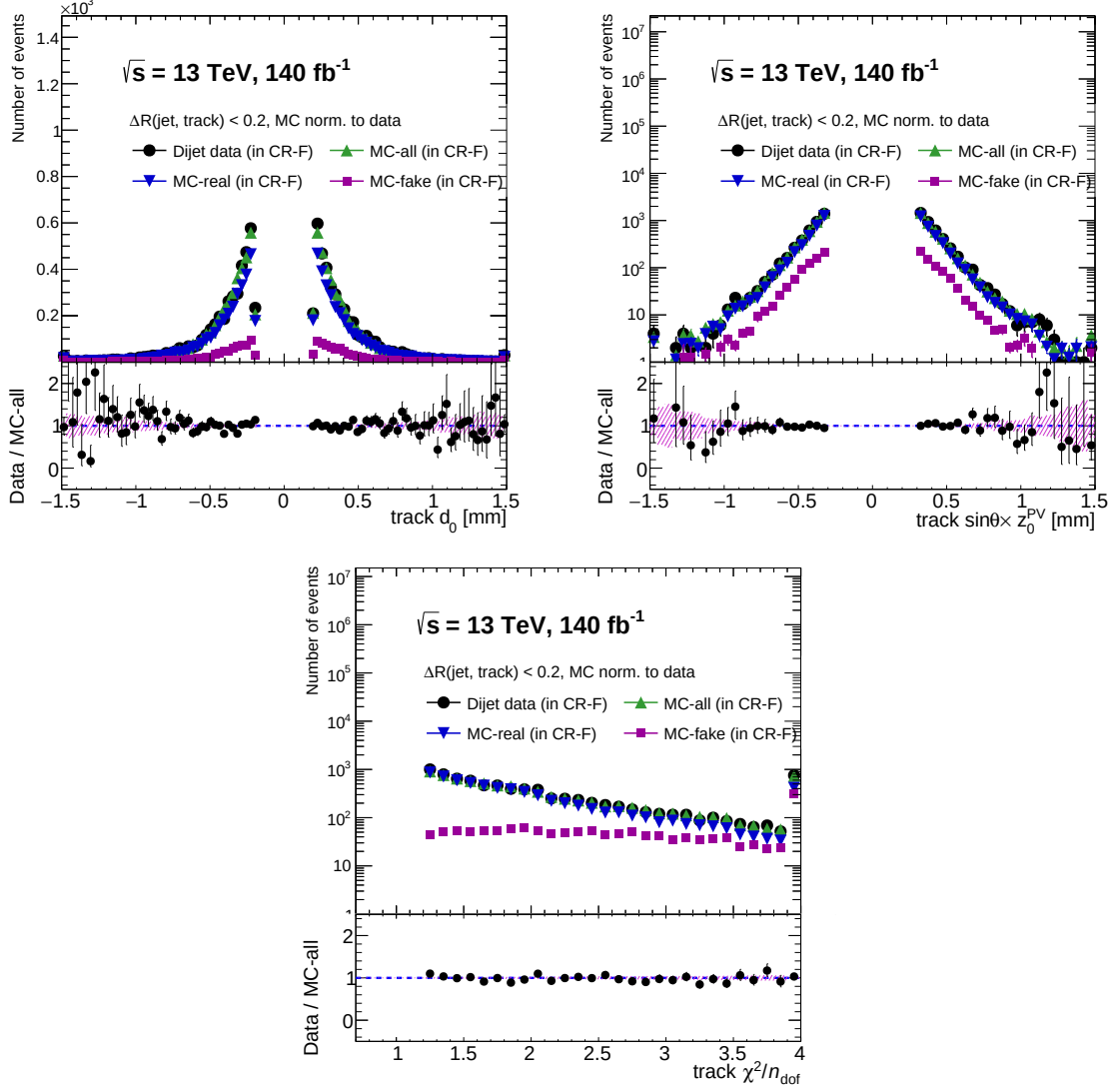


Figure 5.9: Distributions for LooseWP defined fake enriched CR. The top left plot shows the distribution of the track transverse impact parameter ( $d_0$ ), and the top right plot shows the distribution of  $\sin$  of the theta angle multiplied by the track longitudinal impact parameter computed with respect to the primary vertex. The bottom plot shows the distribution of the track  $\chi^2/\text{DOF}$ . The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalised to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events.

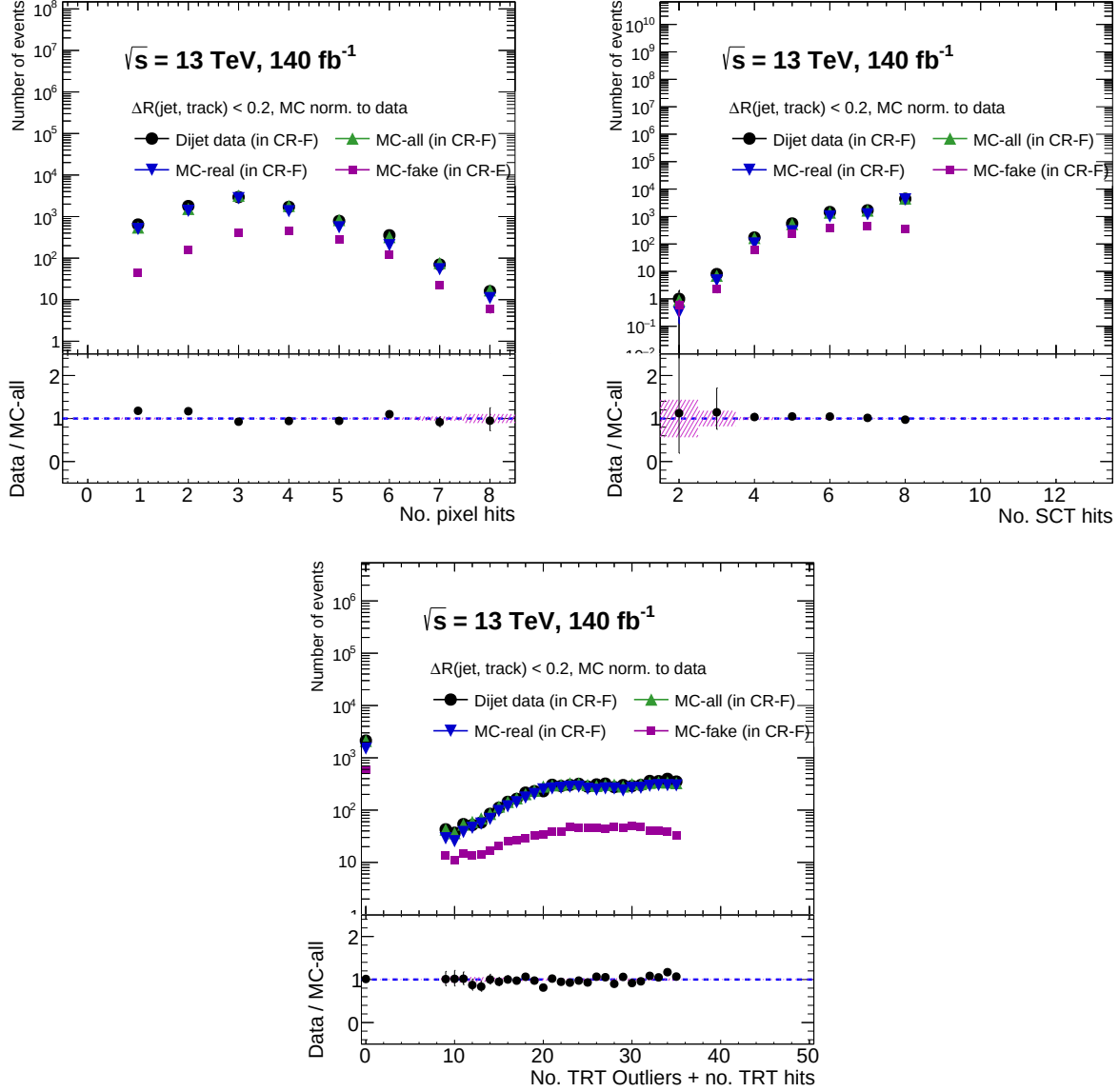


Figure 5.10: Distributions for LooseWP defined fake enriched CR. The top left plot shows the distribution of the number of pixel hits, and the top right plot shows the distribution of the number of SCT hits. The bottom plot shows the distribution of the number of TRT Outliers plus TRT hits. The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalised to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events.

|                                                                      | $N_{\text{tracks}}^{\text{data}}$ | $\frac{F_{\text{trk}}}{R_{\text{trk}}} [\%]$ | $\epsilon \text{ data} [\%]$ | $\epsilon \text{ MC} [\%]$ |
|----------------------------------------------------------------------|-----------------------------------|----------------------------------------------|------------------------------|----------------------------|
| pre-selection                                                        | 62779254                          | 0.109                                        | -                            | -                          |
| $+ d_0  > 0.2$                                                       | 479069                            | 3.653                                        | 0.8                          | 0.7                        |
| $+\sin\theta \times  z_0^{\text{PV}}  > 0.3$                         | 31233                             | 7.131                                        | 6.5                          | 6.2                        |
| $+\text{track}\chi^2/\text{DOF} \geq 1.2$                            | 14357                             | 15.489                                       | 46.0                         | 45.7                       |
| $+n_{\text{SCT}} < 9, +n_{\text{Pixel}} > 0$                         | 10062                             | 19.875                                       | 70.1                         | 70.4                       |
| $+(n_{\text{TRT}} + n_{\text{TRT Outliers}}) < 36 (\text{final CR})$ | 8322                              | 22.150                                       | 82.7                         | 83                         |

Table 5.3: Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), ratio between the number of fake and real tracks ( $F_{\text{trk}}/R_{\text{trk}}$  in the simulation) and the selection efficiency of each criterion ( $\epsilon$ ) in data and MC simulation for the LooseWP.

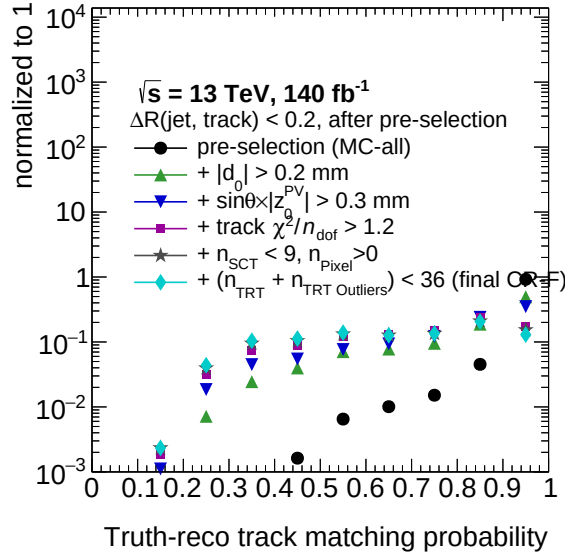


Figure 5.11: The distribution for LooseWP of the truth-reco track matching probability after the pre-selection (black dots) and after each requirement used to define the control region enriched in fake track (coloured markers). Distribution obtained with MC simulation. Only the statistical uncertainties are shown.

## 5.4 Discussion on results

### 5.4.1 Fraction of fake tracks using reprocessed Run2 Data and corresponding MC Samples

Figure 5.12 illustrates the fitting results of the distribution for some variables, specifically for the LooseWP. The fit results match the observed data within the **CR**. A detailed summary of the fitted results for the LooseWP is shown in Table 5.4. The fitted fraction of **FT** in the **CR** ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) is observed to vary between 15% to 23%, depending on the fitting variable.

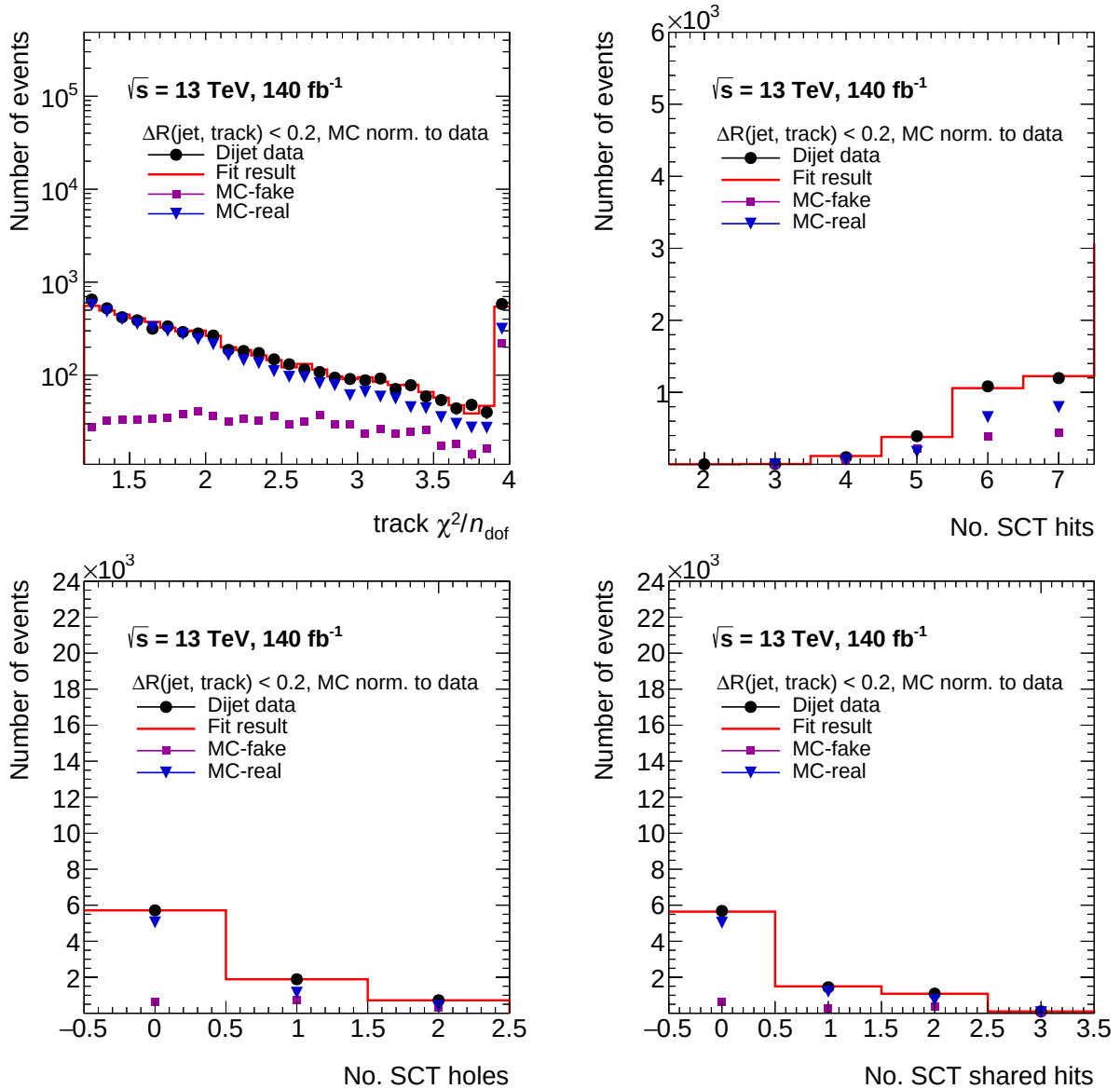


Figure 5.12: The good performance of the fit (red line) in the control region enriched in fake track for LooseWP. Data (back dots), MC real tracks (blue down-triangles), and MC fake track (magenta squares) distributions are also shown. The last bin includes overflow. Only the statistical uncertainties are considered.

| Selected variable            | $f_{\text{CR MLE}}^{\text{fakeTrk}}$ | $f_{\text{CR Toys}}^{\text{fakeTrk}}$ | $f_{\text{CR Histo}}^{\text{fakeTrk}} \chi^2/\text{DOF}$ |
|------------------------------|--------------------------------------|---------------------------------------|----------------------------------------------------------|
| track $\chi^2/\text{DOF}$    | $0.1591 \pm 0.0151$                  | $0.1678 \pm 0.0141$                   | $0.1675 \pm 0.0145$                                      |
| $n_{\text{SCT hits}}$        | $0.2287 \pm 0.0154$                  | $0.2166 \pm 0.0151$                   | $0.2171 \pm 0.0149$                                      |
| $n_{\text{SCT holes}}$       | $0.208 \pm 0.0142$                   | $0.2019 \pm 0.0142$                   | $0.2019 \pm 0.0144$                                      |
| $n_{\text{SCT shared hits}}$ | $0.1571 \pm 0.0173$                  | $0.1472 \pm 0.0186$                   | $0.1471 \pm 0.0191$                                      |

Table 5.4: **LooseWP**. The fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) along with the corresponding statistical uncertainty after fitting the chosen distributions. The outcomes of the 1000 toy experiments and the minima of the  $\chi^2/n_{\text{DOF}}$  from the data and MC histograms of these variables are presented.

To assess the ability of different variables to distinguish between fake and real tracks, Figure 5.13 shows a comparison between the data and the **MC** simulation using a  $\chi^2$  test for the **LooseWP** selection. In this investigation, the fraction “f” of **FT** in the **MC** simulation was manually varied from 0 (no fake tracks) to 1 (all tracks are fake). For each value of “f”, the  $\chi^2$  between the data and **MC** histograms was calculated. The plot displays  $\chi^2/n_{\text{DOF}}$  as a function of “f”, creating convex curves with a local minimum in the range  $0 \leq f \leq 1$  for each variable. These variables include track  $\chi^2/n_{\text{DOF}}$ , the number of **SCT** hits, **SCT** holes, and **SCT** shared hits. The minima of these curves provide the best estimates for the fraction of fake tracks in the real data and correspond well with the **TFractionFitter** results, as indicated by the colored dots in the figure. Each colored dot highlights the **MLE** of “f” for a given variable, with the fit results yielding estimates of the fake track fraction between 15% and 23%, as indicated in the legend.

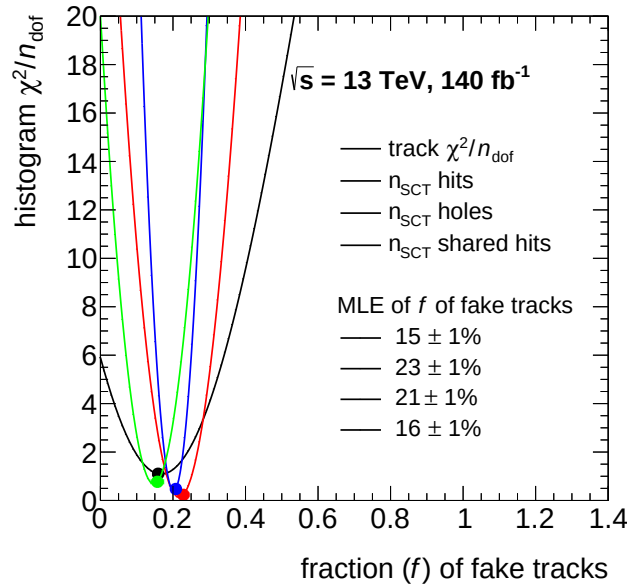


Figure 5.13: **LooseWP**. Data & MC simulation  $\chi^2/n_{\text{DOF}}$  when varying the fraction of fake tracks “f” in the CR. The fit results (Maximum Likelihood Estimation of the fraction of fake tracks) are also shown with coloured dots.

To further verify the accuracy of our statistical uncertainties and fitting method, we conducted 1000 toy experiments. In each experiment, we created pseudo-data by applying random fluctuations to the observed data using a Poisson distribution. At the same time, we varied the **MC** models based on their statistical uncertainties using Gaussian distributions. These tests were analyzed using a likelihood-based method similar to **MLE** and were performed for each discriminant variable to check the stability and potential bias of the fit parameters. The results from these experiments, also listed in Table 5.4, matched the statistical uncertainties obtained through other methods. This consistency confirms that our uncertainty estimates are accurate and that our fitting method is reliable, even when the data and **MC** models experience statistical fluctuations.

The **FT** fractions derived from these three methods are consistent, with the maximum fraction observed at 23% as shown in Table 5.4

Finally, we compared the fitted fraction of **FT** in data to the fraction in **MC**. In the **CR**, 18% of tracks are fake in **MC**, agreeing with the fitted data fraction within 5%, the toy results within 4%, and the  $\chi^2/n_{\text{DOF}}$  results within 4% as well.

However, the fitted fraction of **FT** in data may be affected by the mis-modelling of the variables defining the **CR**, which selects only a small fraction of tracks. Therefore, we extrapolate the **FT** fraction to the pre-selection sample, assuming the **CR** acceptance for **FT** is the same in data and **MC** (approximately 2.05% in **MC**), while making no such assumption for real tracks, for which the **CR** acceptance is much smaller and therefore could be more sensitive to mismodelling. The fraction of **FT** in data for the pre-selection sample can be calculated using the following formula:

$$\frac{1}{2.05\%} \times \frac{f_{\text{CR}}^{\text{fakeTrk}} \times N_{\text{tracks,CR}}^{\text{data}}}{N_{\text{tracks,pre-selection}}^{\text{data}}} \quad (5.1)$$

where  $N_{\text{tracks,CR}}^{\text{data}}$  is the number of tracks in the **CR**, and  $N_{\text{tracks,pre-selection}}^{\text{data}}$  is the number of tracks at the pre-selection level in the data. It is important to note that this method allows us to not depend at all on how well the selection for real tracks in the **CR** is modelled. However, this calculation also assumes that the 2.05% fraction used for normalization is valid in the data. The exact values are provided in Table 5.3.

The fraction of **FT** in data is shown in Tables 5.5, 5.6, and 5.7. The  $f^{\text{fakeTrk}}$  parameter is derived from the fit of the selected distributions, toy experiments, and histogram  $\chi^2/\text{DOF}$ , respectively. As shown in tables, the fraction of **FT** in data listed in the second column ranges from 0.10% to 0.15%. In **MC** simulations, the fraction of **FT** at the pre-selection level is 0.11%. Based on these results, the difference between the fraction of **FT** in data and **MC** is below

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.0010                                | 0.0011                                | -0.06                      |
| $n_{\text{SCT hits}}$        | 0.0015                                | 0.0011                                | 0.36                       |
| $n_{\text{SCT holes}}$       | 0.0013                                | 0.0011                                | 0.23                       |
| $n_{\text{SCT shared hits}}$ | 0.0010                                | 0.0011                                | -0.07                      |

Table 5.5: Fraction of fake tracks at the pre-selection level for the **LooseWP**. The parameter  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$  is derived from the fit of the selected distributions. The table compares the fraction of fake tracks in data and MC and their relative difference.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.0011                                | 0.0011                                | 0.00                       |
| $n_{\text{SCT hits}}$        | 0.0014                                | 0.0011                                | 0.28                       |
| $n_{\text{SCT holes}}$       | 0.0013                                | 0.0011                                | 0.12                       |
| $n_{\text{SCT shared hits}}$ | 0.0010                                | 0.0011                                | -0.12                      |

Table 5.6: Fraction of fake tracks at the pre-selection level for the **LooseWP**. The parameter  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$  is derived from the toy experiments. The table compares the fraction of fake tracks in data and MC and their relative difference.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.0011                                | 0.0011                                | -0.01                      |
| $n_{\text{SCT hits}}$        | 0.0014                                | 0.0011                                | 0.29                       |
| $n_{\text{SCT holes}}$       | 0.0013                                | 0.0011                                | 0.20                       |
| $n_{\text{SCT shared hits}}$ | 0.0010                                | 0.0011                                | -0.09                      |

Table 5.7: Fraction of fake tracks at the pre-selection level for the **LooseWP**. The parameter  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$  is derived from the histogram  $\chi^2/\text{DOF}$ . The table compares the fraction of fake tracks in data and MC and their relative difference.

37%, as shown in the table’s last column.

## 5.4.2 Systematic Uncertainties

This section will describe the uncertainties associated with the study presented in this chapter, focusing on the rate of reconstructing **FT** in dense environments.

### Fake Track Reconstruction Uncertainty

For a  $\Delta R(\text{jet}, \text{track}) < 0.2$  selection, the discrepancy between the fraction of **FT** passing the **LooseWP** or the **TightPrimaryWP** in data and **MC** simulations is found to be 37%. This level of agreement is consistent across different track selections and dense environment conditions,



supporting the reliability of our results.

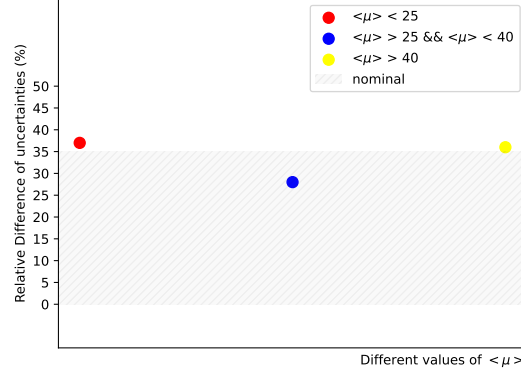


Figure 5.14: Overall uncertainties in the fake track fraction modelling determined in separate bins of  $\langle \mu \rangle$ , compared to the inclusive measurement.

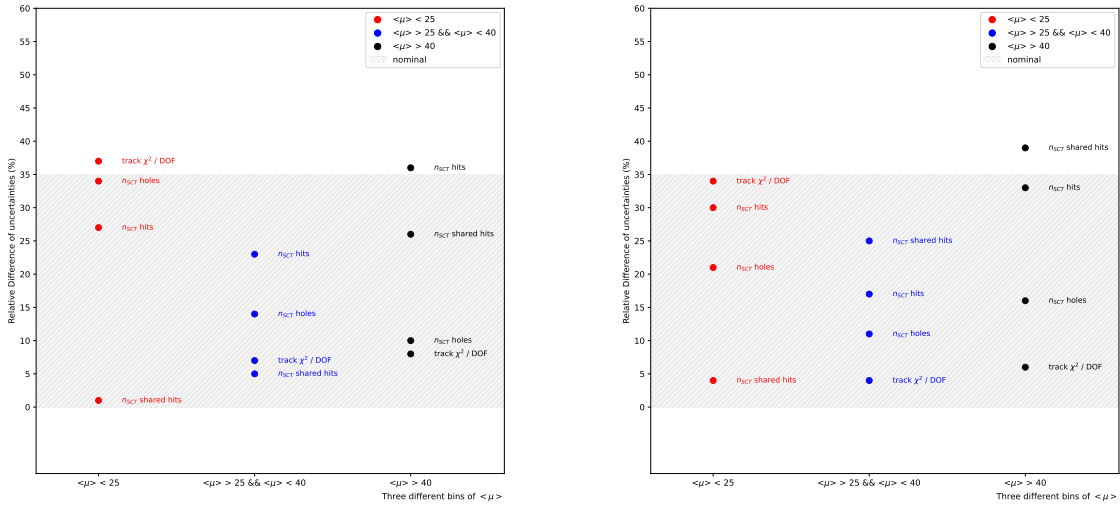


Figure 5.15: Overall uncertainties in the fake track fraction modelling determined from each selected variable in separate bins of  $\langle \mu \rangle$ , compared to the inclusive measurement.

### Dependence on the average number of interactions per bunch crossing $\langle \mu \rangle$

The uncertainties were also analysed in three non-overlapping bins of  $\langle \mu \rangle$ . The maximum difference between data and MC in these bins is around 35%, as shown in Figures 5.14 and 5.15. These figures demonstrate that the uncertainties obtained from measurements in different  $\langle \mu \rangle$  bins are usually within the assigned 35%. Additional details are given in appendix B.

## Conservative Uncertainty Estimate

Based on the results obtained from this study at  $139 \text{ fb}^{-1}$  of Run 2  $pp$  collisions data, the proposed conservative uncertainty is 35% on the rate of reconstructing **FT** in dense environments. This estimate is assumed to be independent of track  $p_T$ ,  $|\eta|$ , and  $\Delta R(\text{jet}, \text{track})$ . This uncertainty also accounts for potential differences between the **FT** sources selected at the pre-selection level and those in the CR-F used in this study, as well as those present in various **ATLAS** analyses.

## Consistency with previous Results

The derived uncertainty is consistent with the uncertainty on the **FT** from the preliminary **rel22** results, as detailed in Ref. [126]. Figures 5.14 and 5.15 support these conclusions, showing that the uncertainties obtained from measurements in different  $\langle\mu\rangle$  bins generally fall within the assigned 35%.

In summary, the uncertainties associated with the rate of **FT** reconstruction using the **LooseWP** and the **TightPrimaryWP** track selections in dense environments are well-characterised and conservatively estimated to be 35%.

## 5.5 Summary

---

The rate of **FT** is measured using data at a luminosity of  $139 \text{ fb}^{-1}$  from Run 2 proton-proton collisions at the **ATLAS** experiment, with reprocessed samples from **rel22**. A **CR** is defined by inverting track quality requirements, leading to an increased rate of **FT**. The fraction of **FT** in this **CR** is determined from data by a template fit, using fake and real tracks templates derived from **MC** simulations. This fraction is between 16-23%, depending on the distribution being fitted. This result is cross-checked by studying the chi-squared ( $\chi^2$ ) values computed between the data and **MC** histograms and with a 1000 toy experiments study.

This fraction of **FT** is further extrapolated outside the **CR** using the **CR** acceptance (approximately 2%) determined from **MC** simulations. After the pre-selection, the fraction of **FT** in the full data sample is between 0.10-0.14%, while in **MC** simulations, it is 0.11%. A conservative modelling uncertainty of 35%, accounting for the differences between data and **MC** simulations, is assigned based on the spread of fitted values and the impact of varying the **CR** definition.

The results discussed in this chapter are detailed in the **ATLAS** internal document, Ref.

[119]. I am one of the three main authors of this document, and my primary role was as a main analyser. My work focused on completing the measurements of the **FT** for the entire Run 2 dataset. This involved thoroughly verifying and finalising the statistical uncertainties linked to these measurements. Additionally, I contributed to the maintenance of the common software used in our analysis by fixing bugs, improving some scripts, and enhancing the visual quality of the plots.

# Chapter 6

## A first exercise in reinterpreting search results with monojet+MET events

### Contents

---

|            |                               |            |
|------------|-------------------------------|------------|
| <b>6.1</b> | <b>Context and Motivation</b> | <b>101</b> |
| <b>6.2</b> | <b>General strategy</b>       | <b>102</b> |
| <b>6.3</b> | <b>Discussion on Results</b>  | <b>104</b> |
| <b>6.4</b> | <b>Summary</b>                | <b>107</b> |

---

### 6.1 Context and Motivation

---

An essential signature for studying **BSM** physics involving final states characterized by an energetic jet and missing transverse momentum  $p_T^{\text{miss}}$  (with its magnitude being the missing transverse energy  $E_T^{\text{miss}}$ ) was searched by both **CMS** [127] and **ATLAS** Collaboration [128]. The data analyzed in these two papers are collected during the proton-proton collision collision at 13 TeV. This signature is crucial for many **BSM** searches, **SUSY** and especially those targeting **Weakly Interacting Massive Particles (WIMP)** as candidates for **DM**. In the published paper by **ATLAS** (which provides the results reinterpreted here), many **Signal Regions (SRs)** were considered (see Table 6.1) by imposing increasing cuts on  $E_T^{\text{miss}}$ . Model-independent upper limits on **BSM** signal contributions to the **SRs** at the 95% **Confidence level (CL)** were obtained, outlined in [129]. These upper limits were used to interpret the results within the context of various **BSM** models. The models considered include pair-produced weakly interacting dark-matter candidates, large extra spatial dimensions, and supersymmetric

particles in several compressed scenarios.

However, our main interest is **SUSY**. The ATLAS publication provides interpretations of the results in terms of constraints on the production of squark-antisquark pairs. When the mass difference between squarks and neutralino is small, the resulting decay products (the quark and the neutralino) will have low kinetic energy, leading to low transverse momentum ( $p_T$ ) jets and low missing transverse energy ( $E_T^{\text{miss}}$ ). Thus, final state jets can not be used to identify the signal events. Signal sensitivity is, however, regained by exploiting events with significant initial state radiation jets, which leads to a large amount of missing transverse energy originating from the undetected decay products of the recoiling squarks. Indeed, most of the squark momentum is carried away by the neutralino when the latter is heavy. Therefore, the experimental signature of one energetic jet and missing transverse momentum is particularly well suited to search for such scenarios.

In this analysis, we use the same published model-independent upper limits to set exclusion limits on the gluinos masses. For this purpose, we generate simulated events while considering gluinos as the produced sparticles instead of squarks, as shown in Figure 6.1. The general strategy to produce events for such topology and further treatment on them to exclude gluino mass will be explained in Section 6.2. In Section 6.3, we will present our results along with the consideration of uncertainties, and in Section 6.4, we will give our concluding remarks.

| Signal Regions            | SR0   | SR1   | SR2   | SR3    | SR4    | SR5    | SR6   |
|---------------------------|-------|-------|-------|--------|--------|--------|-------|
| $E_T^{\text{miss}}$ [GeV] | > 200 | > 250 | > 300 | > 350  | > 400  | > 500  | > 600 |
|                           | SR7   | SR8   | SR9   | SR10   | SR11   | SR12   |       |
|                           | > 700 | > 800 | > 900 | > 1000 | > 1100 | > 1200 |       |

Table 6.1: Illustration of Signal Region bins for increasing cuts on  $E_T^{\text{miss}}$  [128]

## 6.2 General strategy

MC event samples were produced at  $\sqrt{s} = 13$  TeV through MADGRAPH5\_AMC@NLO (v3.3.2) [97], interfaced with PYTHIA8 (v.8306) [98] and DELPHES (v.3.5.0) [130]. The leading-order matrix elements included up to two additional partons. Showering and hadronization are handled by PYTHIA8 using the NNPDF23LO PDF set [131] with multiparton interaction on. The **ATLAS** detector's response is emulated using the characteristics of the pileup card in DELPHES. Each sample has 100,000 events, with neutralino mass ranging from 590 to

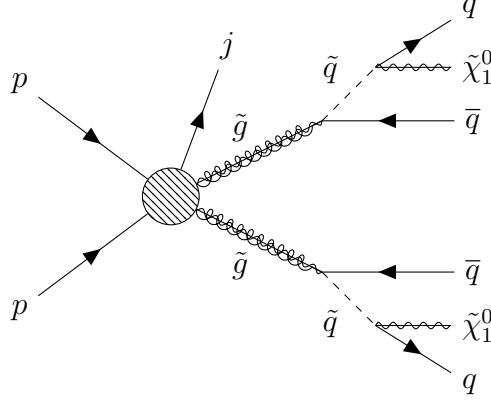


Figure 6.1: A generic Feynman diagram for the pair production of gluinos with the decay mode of  $\tilde{g} \rightarrow \bar{q} + q + \tilde{\chi}_1^0$  and a jet from initial-state radiation is indicated as illustration purposes.

1015 GeV and gluino mass going from 600 to 1025 GeV. The neutralino-gluino mass difference goes from  $\Delta m = 5$  GeV to  $\Delta m = 150$  GeV. The CKKW-L matching prescription [132] was used, the matching scale being fixed at 250 GeV following standard conventions as the edge of the sensitivity is reached around 1 TeV gluinos.

Each event passed a set of selection criteria for generated **MC** samples, particularly focusing on constraints related to jets, specified in Table 6.2, as outlined in Ref. [128]. The variable  $p_{\text{T}}^{\text{recoil}}$  represents the transverse momentum balancing the observed jet in the event. Each event was properly weighted with a scale factor  $S_f(i)$  considering luminosity (remained fixed for all cases at  $140 \text{ fb}^{-1}$ ) and cross-section from Ref. [133] also published in Ref [134] (based on the gluino mass provided during generation) as given

$$S_f(i) = \frac{w_i \times \text{luminosity} \times \text{cross-section}}{\sum_{i=1}^N w_i} \quad (6.1)$$

where  $N$  is the total number of events, and  $w_i$  is the weight of the  $i^{\text{th}}$  **MC** generated event. Further, for every neutralino-gluino mass point, we calculated the number of events for each

Table 6.2: Selection criteria for signal region events

| Criteria                                                           | Description                                                                                |
|--------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Jets                                                               | up to 4 with $p_{\text{T}} > 30 \text{ GeV}$ , $ \eta  < 2.8$                              |
| $ \Delta\phi(\text{jets}, \mathbf{p}_{\text{T}}^{\text{recoil}}) $ | $> 0.4$ ( $> 0.6$ if $200 \text{ GeV} < E_{\text{T}}^{\text{miss}} \leq 250 \text{ GeV}$ ) |
| Leading jet                                                        | $p_{\text{T}} > 150 \text{ GeV}$ , $ \eta  < 2.4$                                          |

**SRs** bin. We listed the **SRs** bins where the computed number of events exceeds the model-independent upper limit provided in Ref. [128]. Then, we looked for the bin with the highest excess events beyond the upper limit. For this bin, we determined precisely the minimal excluded cross-section (assuming signal acceptance invariance for small mass variations) by

multiplying the nominal cross-section by the inverse of the ratio of the expected number of events to the upper limit of events. Then, we identified the gluino mass corresponding to this cross-section value using the table provided by Ref. [133]. Using this procedure, we found the excluded mass points. Finally, we drew a contour connecting these points, indicating which region in the gluino-neutralino mass plane is excluded.

### 6.3 Discussion on Results

Figure 6.2 shows the final exclusion limits. Results are presented as a function of gluino mass vs. gluino-neutralino mass difference. In the figure, we display the exclusion limits we have

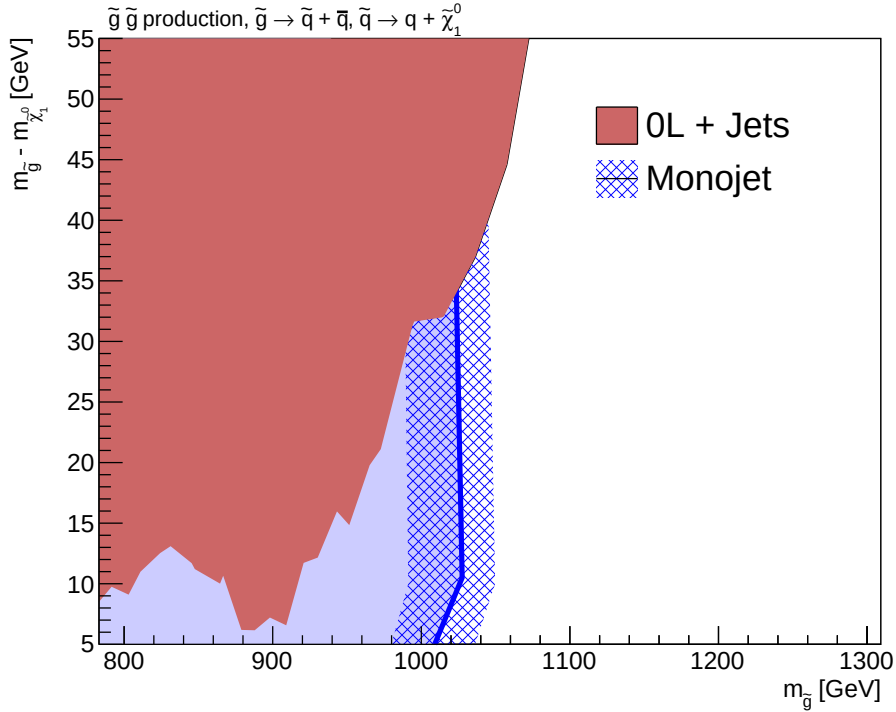


Figure 6.2: Exclusion region at 95 % **CL** as a function of  $m_{\tilde{g}}$  and  $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$  mass difference for  $\tilde{g}\tilde{g}$  production. The region below 1000 GeV is excluded. Mass differences below 5 GeV are not considered because gluinos become long-lived particles and can hadronize, with non-trivial consequences on production details and interactions with the detector. The dashed lines around observed limits indicated the uncertainties.

calculated and the limit taken directly from a published complementary analysis [135]. Overall, the limits indicated by the solid blue line are provided by our reinterpretation results, and the regions below this line are excluded. In this plane, a major region is already excluded by the OL + Jets analysis [135]. At the same time, our search results illustrate that the monojet analysis excludes a supplementary region of the phase space for small mass differences. The results are also overlaid with an uncertainty band, including the effect of statistical uncertainties, gluino

pair-production cross-section, and jet momentum resolution. The latter three are combined in quadrature to form the uncertainty in the expected **BSM** signal yields:

$$\sigma_{total} = \sqrt{(\sigma_{stat})^2 + (\sigma_{cross})^2 + (\sigma_{jet \text{ resolution}})^2} \quad (6.2)$$

the uncertainty band in Fig. 2 is established using the evolution of cross-sections as a function of mass provided by Ref. [133]. The statistical uncertainties are calculated through a simple approach such that for all number of events, it is given as

$$\sigma_{stat} = \sqrt{\sum_{i=1}^N S_f^2(i)} \quad (6.3)$$

where  $S_f(i)$  is defined in equation (6.1). The uncertainties in the signal production cross-section are taken from the gluino-gluino production cross-sections computed in the following approximations: NNLO<sub>approx</sub> + NNLL [134] which are almost 11.5 % in each case for our selected gluinos mass points.

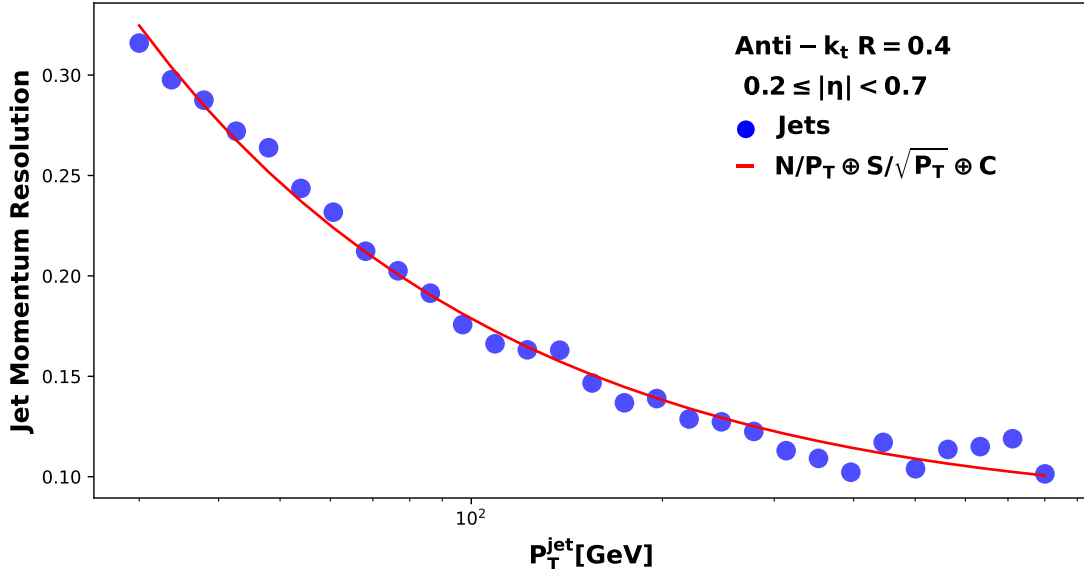


Figure 6.3: Relative jet momentum resolution as a function of  $p_T$ , for central jets. The expectation from the Monte Carlo simulation based on DELPHES and used in this paper is compared with the best fit of a common jet momentum resolution parameterisation.

Our third uncertainty lies in the jet momentum resolution, which is significant when studying BSM physics because it impacts the missing transverse momentum. The jet momentum resolution is a function of the jet's transverse momentum, with three independent contributions



representing the resolution of the detector’s calorimeters.

$$\text{Relative Jet momentum resolution} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C \quad (6.4)$$

In this expression, ‘N’ stands for the noise term (electronics and pileup), ‘S’ denotes the sampling term, which is inversely proportional to the square root of the jet’s transverse momentum, and the constant ‘C’ term defines variations representing a steady percentage of the jet’s transverse momentum. To evaluate the jet momentum resolution, we first identify the closest jet to each generated jet, imposing a constraint that the angular distance between them should be less than 0.4 and primarily focusing on central jets. Then, we look at how well the jets match the generated jets as a function of transverse momentum  $p_T$ . Additionally, we find the spread of the jet’s  $p_T$  from the generated jet’s  $p_T$  as depicted by blue solid circles in Figure 6.3.

We fitted the equation of Jet momentum resolution on our **MC** expectation points to determine the values of the sampling term ‘S’ and the constant term ‘C’. Further, these values were compared with the jet momentum resolution curve given in **ATLAS** publication [136] for a similar pseudorapidity interval to assess the differences in these parameters. Specifically, we observed that our values for the sampling term ‘S’ were 50% higher and the constant term ‘C’ were 60% higher compared to the **ATLAS** values. Subsequently, we adjusted the jet energy resolution in the DELPHES detector configuration by scaling ‘S’ by 50% and ‘C’ by 60% for both the **ECAL** and **HCAL** resolution formulae. We reproduced a simulated sample with these alternative parameters by redoing the whole generation. However, the same random generator seed was used, meaning the original and varied samples were not statistically independent. This is beneficial, as it avoids statistical fluctuations from causing artificial differences between the two compared samples. We compared the exclusion limits obtained in that case. For instance, for the mass point  $\text{neutralino} = 995 \text{ GeV}$  and  $\text{gluino} = 1000 \text{ GeV}$ , the original yield was  $1.08^{+1.15}_{-1.01}$ . The adjusted parameters changed the yield to  $1.25^{+1.41}_{-1.10}$ . The difference in sensitivity gives us a conservative uncertainty to cover for the mismodelling of the jet energy response in DELPHES. The relative contributions of all three uncertainties can be understood by comparing their magnitudes. The term  $\sigma_{stat}$  is calculated based on the statistical fluctuations in the number of events. The magnitude of this uncertainty depends on the size of the dataset, and this term generally contributes the least to the total uncertainty due to the relatively large number of events analyzed. On the other hand, the gluino pair-production cross-section uncertainty is moderate, providing a substantial but smaller contribution compared to the jet resolution uncertainty.

## 6.4 Summary

---

To summarize, it is possible to broaden the scope of the search for supersymmetric gluinos in events involving a high-momentum jet and missing transverse momentum. It complements a similar-purposed reinterpretation analysis presented in Ref. [137], which also targets gluino signatures. In the latter study, the main sensitivity is provided by the **SRs** of the 0L+jets analysis [135], while our work evaluates explicitly the impact of the monojet analysis alone [128].

We show that the excluded region in the gluino mass spectrum can be significantly expanded by directly exploiting model-independent upper limits and methods developed in earlier investigations aimed at the exclusion limits for squarks. In contrast, the referenced work [137] appears to use signal and published background yield distributions to redo a statistical analysis of the observations. Our exclusion plot, displayed in the mass plane of the gluino vs. gluino-neutralino mass difference, shows exclusion limits raised to 1000 GeV for low gluino-neutralino mass differences, which were not explicitly ruled out by the original **ATLAS SUSY** searches.

Compared to Ref. [137], a fundamental difference in our analysis is evaluating the impact of various uncertainties in signal prediction. Specifically, our results are presented with three different types of uncertainties, with the most dominant being from jet momentum resolution. This provides a useful illustration of the potentially limited accuracy of reinterpretation studies, which primarily rely upon emulating actual detector responses with Delphes.

The research work discussed in this chapter has been published within Rom. J. Phys. [138]. I am one of the two main authors of this paper. The analysis is essentially divided into two parts. My colleague, the second author of the paper, managed the **MC** to produce events. My contributions included coding for a detailed analysis, conducting a cut-and-count study of the events, and creating the final exclusion plots with a survey of statistical and systematic uncertainties. I also contributed to the majority of the writing tasks for the paper.

# Chapter 7

## Interpretation of ATLAS Run II SUSY searches in the context of pMSSM

### Contents

---

|            |                                                                                    |            |
|------------|------------------------------------------------------------------------------------|------------|
| <b>7.1</b> | <b>Context and Motivation</b>                                                      | <b>109</b> |
| <b>7.2</b> | <b>Methodology</b>                                                                 | <b>110</b> |
| 7.2.1      | Software Framework and External Constraints                                        | 110        |
| 7.2.2      | General pMSSM Scans                                                                | 116        |
| <b>7.3</b> | <b>Run 2 ATLAS supersymmetric searches used for Interpretation</b>                 | <b>118</b> |
| <b>7.4</b> | <b>Analysis Results</b>                                                            | <b>120</b> |
| 7.4.1      | LSP Mass Constraints                                                               | 121        |
| 7.4.2      | ATLAS constraints on the strong production side                                    | 122        |
| 7.4.3      | ATLAS constraints on the electroweak production side                               | 130        |
| 7.4.4      | Complementarity with Dark Matter Detection Experiments                             | 136        |
| 7.4.5      | Complementary and Overlap of ATLAS Experiment Constraints with<br>Other Experiment | 137        |
| <b>7.5</b> | <b>Summary</b>                                                                     | <b>141</b> |

---

In this chapter, I will present my own results after introducing the general concept of **pMSSM** scans. For the general description, I used the following bibliographic sources:

- ATLAS Collaboration, “The quest to discover supersymmetry at the ATLAS experiment” [139]
- ATLAS Collaboration, “ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the **pMSSM**” [140]

## 7.1 Context and Motivation

---

During the **LHC**’s Run 1 and Run 2 phases, both **ATLAS** and **CMS** experiments extensively searched for **SUSY** signatures. Since no clear deviations from the **SM** were found, stringent constraints were imposed on the parameters of simplified models. However, these simplified models have only a few free parameters and do not cover the entire **MSSM** parameter space. As discussed in Section 2.5, the **MSSM** has a high degree of freedom, making direct constraints on its parameters impractical. The 19D **pMSSM** model [141] offers a practical simplification of the **MSSM** by reducing it to 19 free parameters, allowing for the possibility of constraining this model. Constraining the 19D **pMSSM** model helps evaluate the **ATLAS** experiment’s limitations and exclusions for more realistic **SUSY** models, providing valuable insights for future **SUSY** searches.

During the Run 1 phase, the **ATLAS** experiment reinterpreted **SUSY** search data by sampling 300,000 **pMSSM** models [142]. The **CMS** experiment also employed a global Bayesian statistical approach for parameter space sampling and reinterpretation, demonstrating strong constraints on squark and gluino masses [143]. In the Run 2 phase, focusing on the weakly constrained **EW SUSY** particles from Run 1, the **ATLAS** experiment reinterpreted data in five-dimensional parameter space  $(M_1, M_2, \mu, m_A, \tan\beta)$  [144], showing limited exclusion power for low-mass **EW SUSY** particles [140]. This study uses **ATLAS** results from the Run 2 phase to constrain the **pMSSM** model. Compared to Run 1 studies, this study benefits from improved analyses in **MC** sample simulation, physical object reconstruction, detector performance, higher centre-of-mass energy and integrated luminosity in Run 2. Additionally, it utilises new software developed by the **ATLAS** collaboration, including the **SIMPLEANALYSIS** framework [145], workspace storage [146], the **RECAST** [147, 148] and **REANA** reinterpretation frameworks [149]. The latest **ATLAS SUSY** Run2 results are also summarized in Ref. [139].

This chapter uses information from the **ATLAS** Run 2 searches to analyse the constraints **ATLAS** imposes on the **pMSSM**. The outcomes of this study will provide an overview of **EW**

and strong **SUSY** after **ATLAS** Run 2. The structure of this chapter is as follows. Section 7.2 describes the analysis procedure used to sample the **pMSSM** and evaluate the resulting models using **ATLAS** searches. The “General **pMSSM** Scan” detailed in section 7.2.2 motivates the ranges assigned to the 19 **pMSSM** parameters. Section 7.3 offers an overview of the **ATLAS SUSY** Run 2 searches and other non-**ATLAS** searches used for interpretation. The analysis results are presented in section 7.4, starting with constraints on the **LSP** mass, followed by strong and **EW** production constraints. This section also discusses how the results relate to **DM** and the overlap of **ATLAS** results with other experiments. Finally, the concluding remarks are given in section 7.5.

## 7.2 Methodology

The following section will introduce the analysis strategy of this study, including the software framework, simulated samples, scanning of **pMSSM** model parameters, and the adopted experimental agreements.

### 7.2.1 Software Framework and External Constraints

The sampling strategy for the parameter space of **pMSSM** in this analysis involves uniform sampling within the parameter space of interest. Figure 7.1 shows the workflow for determining whether a sampled **pMSSM** model is excluded. The **pMSSM** model is first analysed through several programs to calculate the physical observables as summarised in Table 7.1.

| Program                      | Version | Purpose                                                                                                                                                                                                                                                                                                                                                                                     |
|------------------------------|---------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>SPheno</b> [150, 151]     | 4.0.5   | Calculates the mass spectrum by determining the precise masses of all supersymmetric particles predicted by the model. Additionally, it computes, the branching ratios describe the probabilities of these <b>SUSY</b> particles decaying into specific sets of <b>SM</b> or other <b>SUSY</b> particles. SPheno also calculates the electroweak observables, such as the $\rho$ parameter. |
| <b>FeynHiggs</b> [152–158]   | 2.18.0  | Calculates the mass and branching ratios of particles in the Higgs sector of the <b>MSSM</b> model such as the masses and branching fractions of the supersymmetric and <b>SM</b> Higgs bosons.                                                                                                                                                                                             |
|                              | 2.19.1  | Calculates the mass of the charged Higgs in the <b>MSSM</b> . Additionally, FeynHiggs recalculates the W boson mass, which is used as a constraint in the analysis.                                                                                                                                                                                                                         |
| <b>MicrOMEGAs</b> [159, 160] | 5.2.1   | Calculates the <b>DM</b> relic density ( $\Omega h^2$ ) assuming <b>LSP</b> as <b>WIMP</b> particles. This program also calculates the scattering cross-section of <b>WIMP</b> -nucleons, both spin-dependent (SD) and spin-independent (SI).                                                                                                                                               |
| <b>SuperISO</b> [161]        | 4.0     | Calculates the branching ratios of various flavour physics processes in the <b>MSSM</b> model. For example, it computes the branching ratio of the rare decay $B_s \rightarrow \mu^+ \mu^-$ .                                                                                                                                                                                               |

Table 7.1: Summary of software tools and their versions used to analyse the **pMSSM** model. Each program is responsible for specific calculations.

If an error occurs during any of the above processes, the model used for analysis will be ex-

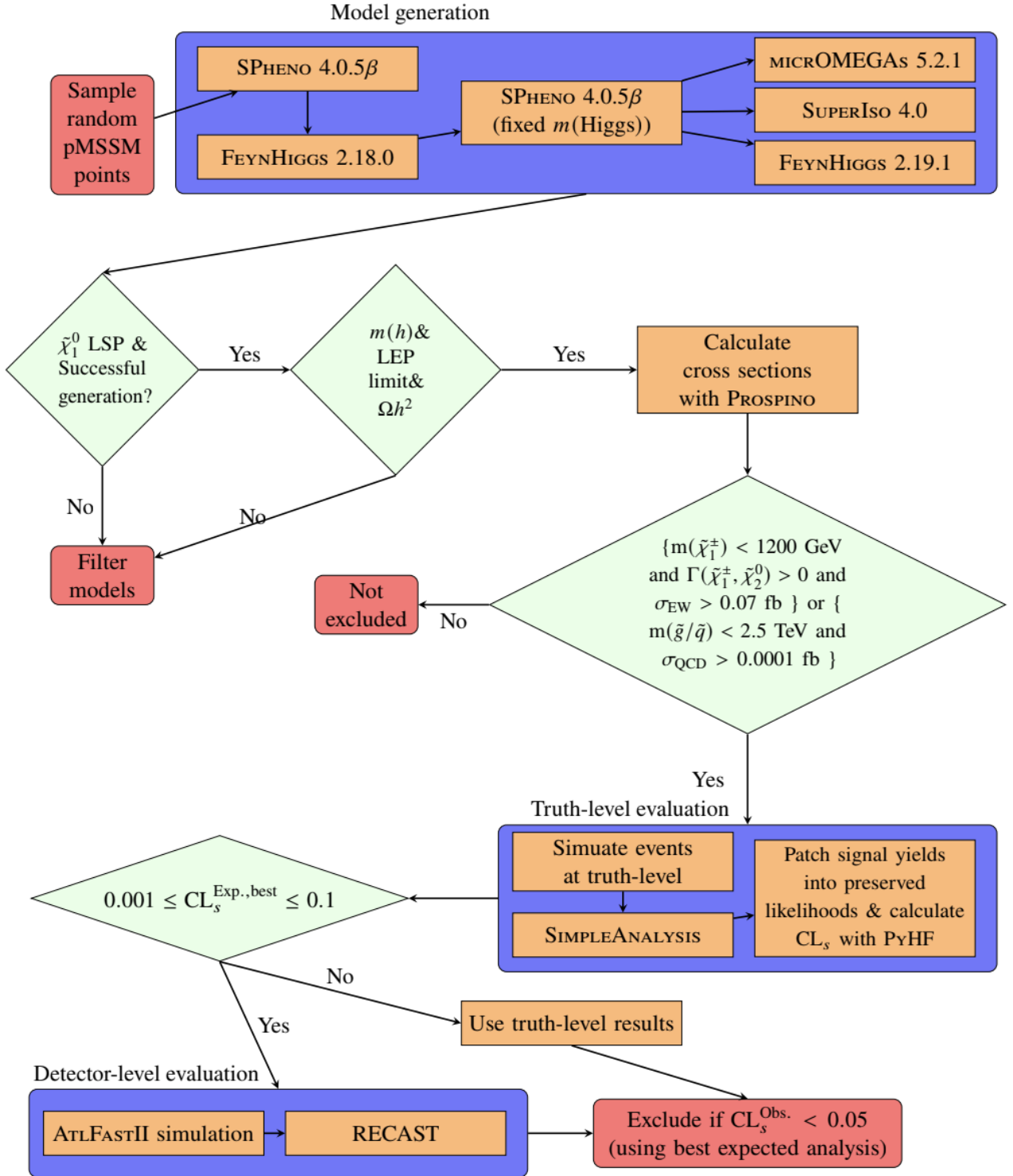


Figure 7.1: Process for the pMSSM scan, starting from sampling the parameter space to evaluating whether each model is excluded [140].

cluded. This type of error likely results from the **SUSY** mass spectrum not meeting theoretical requirements. Subsequently, the analysis will select models assuming the **LSP** should be the lightest neutralino ( $\tilde{\chi}_1^0$ ). The next step is to check if the mass of the lightest Higgs boson  $m(h)$  is close to the **SM** Higgs boson mass:  $m(h) \in [120, 130]$  GeV. This mass range is relatively large because  $\tilde{g}$  contributions to  $m(h)$  are significant when the mass is large, and the theoretical uncertainty on higher-order corrections to the Higgs mass involving gluinos might be greater than 3 GeV [162].

In addition, the model exclusions from other collider experiments are also important. This analysis uses the results of the **LEP** and D0 experiments for preliminary exclusions. In the **EWkino** sector, for mass differences  $\Delta m(\tilde{\chi}_1^+, \tilde{\chi}_1^0) \geq 3$  GeV, models with  $m(\tilde{\chi}_1^+) < 103$  GeV are excluded. If the mass difference is less than 3 GeV, models with  $\tilde{\chi}_1^+$  mass less than 91.9 GeV are excluded.

In the context of the gluino ( $\tilde{g}$ ) search, the D0 experiment utilized the **cMSSM** model [163, 164]. Since the parameter space of the **pMSSM** encompasses that of the **cMSSM**, applying the D0 experimental results directly to the **pMSSM** could lead to the exclusion of certain parameter regions. Specifically, this would result in excluding models where the gluino mass is less than 200 GeV.

| Constraint                                             | Lower bound           | Upper bound                  | Comments                                                                                                                                                                                                            |
|--------------------------------------------------------|-----------------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| BR( $b \rightarrow s\gamma$ )                          | $3.11 \times 10^{-4}$ | $3.87 \times 10^{-4}$        | 2022 PDG average ( $2\sigma$ window) [165]                                                                                                                                                                          |
| BR( $B^+ \rightarrow \tau\nu$ )                        | $6.10 \times 10^{-5}$ | $1.57 \times 10^{-4}$        | 2022 PDG average ( $2\sigma$ window) [165]                                                                                                                                                                          |
| BR( $B_s \rightarrow \mu\mu$ )                         | $1.87 \times 10^{-9}$ | $4.31 \times 10^{-9}$        | Most recent LHCb result ( $2\sigma$ window) [166]                                                                                                                                                                   |
| $\delta\rho$                                           | -0.0004               | 0.0018                       | The global electroweak fit has been updated by the <b>GFit</b> group [167] (excluding the CDF $W$ -mass measurement [168])                                                                                          |
| $\Gamma_{\text{inv}}(Z)$                               | -                     | 2 MeV                        | High-precision electroweak measurements at the $Z$ -resonance were conducted by experiments at the SLC and LEP colliders [169].                                                                                     |
| $m(W)$                                                 | 80.347 GeV            | 80.407 GeV                   | 2022 PDG result (excluding the CDF $W$ -mass measurement [165, 168] and using a $2\sigma$ window, expanded by 6 MeV to account for uncertainty arising from the top-quark mass in the MSSM Higgs calculation [170]) |
| DM relic density                                       | N/A                   | 0.12                         | The most recent constraint from Planck [171]                                                                                                                                                                        |
| DM Direct Detection $\sigma_{\text{Spin-independent}}$ | N/A                   | varying with $m(\text{LSP})$ | Exclusion contour provided by the LZ [172]                                                                                                                                                                          |
| DM Direct Detection $\sigma_{\text{Spin-dependent}}$   | N/A                   | varying with $m(\text{LSP})$ | Exclusion contour provided by PICO-60 [173]                                                                                                                                                                         |

Table 7.2: External constraints from flavour physics observables, electroweak precision measurements, and Dark Matter searches [140].

This study considers constraints on the **pMSSM** model from both **ATLAS** and non-ATLAS experiments, including indirect searches like the  $W$  boson mass. Table 7.2 summarises these constraints.

For flavor physics, three branching ratios are analyzed:  $B(b \rightarrow s\gamma)$ ,  $B(B_s \rightarrow \mu\mu)$ , and

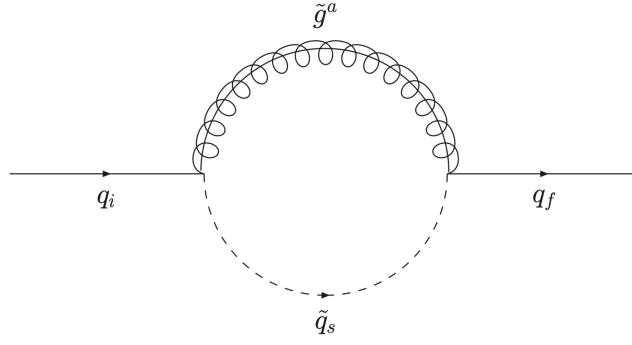


Figure 7.2: Quark self-energy with squark and gluino as virtual particles [174].

$B(B^+ \rightarrow \tau \nu)$ . These are based on the **Particle Data Group (PDG)** global fit and the latest **Large Hadron Collider beauty (LHCb)** results, considering a  $2\sigma$  error range. In **pMSSM** models, the effects of sparticles in loop contributions (one example can found in Figure 7.2) can influence these branching ratios, causing them to differ from experimental results.

For **EW** precision observables, the study considers the  $\rho$  parameter, the invisible decay width of the Z boson ( $\Gamma_{\text{inv}}(Z)$ )<sup>1</sup>, and the W boson mass ( $m(W)$ ). The  $\rho$  parameter, defined as  $\rho = m_W^2 / (m_Z^2 \cos^2 \theta_W)$ , is 1 at tree level in the **SM** [175], but **SUSY** processes can affect this value through loop diagrams. The constraint on  $\rho$  uses results from the GFITTER collaboration [167]. The  $\Gamma_{\text{inv}}(Z)$  constraint is based on results from the SLAC and **LEP** experiments [169]. The  $m(W)$  constraint uses the **PDG** global fit, excluding the CDF result due to its large deviation from other experiments [168]. Additionally, the theoretical uncertainty in calculating  $m(W)$  in the **MSSM** leads to a widened  $2\sigma$  window by 6 MeV.

The constraints from **DM** direct detection experiments include results from the **LUX-ZEPLIN (LZ)** [172] collaboration for spin-independent (SI) interactions and the PICO-60 [173] experiment for spin-dependent (SD) interactions.

For **pMSSM** models that pass the preliminary evaluation, PROSPINO software will be used to calculate the model's cross-section at the **LHC** with next-to-leading order precision. To save computational resources, a pre-screening step is introduced based on expected experimental results before proceeding to detailed simulations. Specifically:

- **Electroweak (EW) Production:** The **EW** production of **SUSY** particles will generally only be simulated if  $m(\tilde{\chi}_1^\pm) \leq 1.2$  TeV. Models where  $m(\tilde{\chi}_1^\pm) > 1.2$  TeV will be excluded at this stage.
- **Strong Interaction Production:** The strong interaction production of **SUSY** particles will generally only be simulated if both  $m(\tilde{g})$  and  $m(\tilde{q}) \leq 2.5$  TeV. Models where both  $m(\tilde{g})$  and  $m(\tilde{q}) > 2.5$  TeV will be excluded at this stage.

<sup>1</sup>This is a measure of the Z boson's decay into particles that do not interact with the detector, such as **LSP**



- **Long-Lived or Stable Particles:** Models with long-lived or stable  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{g}$ , or  $\tilde{q}$  will also not be excluded. Excluding these long-lived models requires specialized experiments designed specifically to search for long-lived particles, which are beyond the scope of this analysis.

In this analysis, the exclusion of **pMSSM** models is conducted through a systematic approach. The procedure involves generating signal samples, performing statistical evaluations, and making decisions based on both truth-level and detector-level analyses. However, in this thesis, only the truth-level results are presented, as the detector-level evaluation is still ongoing. The overall process is as follows:

1. **Signal Generation:** Signal samples for various **pMSSM** models are generated using the MADGRAPH5\_AMC@NLO 2.9.5 generator at leading order [176, 177]. The parton shower and hadronization processes are simulated using PYTHIA8.306 [178].
2. **Truth-Level Evaluation** The truth-level evaluation serves as the initial assessment for the generated models, focusing on computational efficiency and quick exclusion of non-viable models. The process is as follows:

- **Event Simulation:** The events generated in the signal generation step are simulated at the truth level, meaning they are processed without detailed detector effects. This approach significantly reduces computational cost and processing time, allowing for a rapid preliminary evaluation.
- **Events Analysis:** Once the events are simulated, they are analyzed using the SIMPLEANALYSIS framework [145]. The next step is to perform a statistical fit. This fit uses the signal yields obtained from SIMPLEANALYSIS, along with estimates of background yields and observed data for each analysis. Many of the **ATLAS** Run 2 **SUSY** analyses have shared a likelihood file on HEPData [146]. This file, in JSON format, includes the estimated background and observed yields for each analysis region, as well as details on the systematic uncertainties.

**Statistical Evaluation:** The combined data is then subjected to a likelihood-based hypothesis test using the PyHF framework [179]. This framework is designed to handle the complexities of such statistical analyses, producing both observed and expected ( $\mathbf{CL}_{s_{obs}}$  and  $\mathbf{CL}_{s_{exp}}$ ). The results of this test are crucial for determining whether a model should be excluded based on the truth-level evaluation.

- **Exclusion Decision:** The final step in the truth-level evaluation involves making a decision based on the  $\mathbf{CL}_{s_{obs}}$ . If the observed ( $\mathbf{CL}_{s_{obs}}$ ) is found to be less than 0.05, the model is excluded. This threshold ensures that the models with a very low

likelihood of matching the observed data are excluded at this stage. Models that do not meet this exclusion criterion, but fall within the range of  $0.001 \leq CL_{exp} \leq 0.1$ , are flagged for further evaluation at the detector level. These models are referred to as “ambiguous” models.

3. **Ambiguous Models and Detector-Level Evaluation** For cases that require more detailed evaluation, particularly when the  $CL_{exp}$  range is close to exclusion but not decisive, the detector simulations are employed as follows:

- **Detailed Detector-Level Evaluation:** For the ambiguous models, a more detailed evaluation is necessary. This involves subjecting the models to ATLFastII simulation, which includes the effects of the detector. Unlike the truth-level evaluation, this step accounts for the complexities of the detector’s response, providing a more accurate assessment of the model’s viability.
  - **Reproduction of Results:** The models selected for the detector level evaluation are then reproduced using the RECAST and REANA frameworks.
- **Final Exclusion Decision:** If, after the detector-level evaluation, the observed ( $CL_{obs}$ ) is found to be less than 0.05, the model is excluded. This step ensures that only models that cannot be excluded even after a detailed detector-level analysis remain viable candidates for further investigation in the search for **SUSY**.

In summary, the exclusion process for **pMSSM** models in this analysis follows a two-step approach. It begins with a computationally efficient truth-level evaluation, which quickly identifies and excludes non-viable models. Models that are not excluded at this stage are considered “ambiguous” and are subjected to a more detailed detector-level evaluation. If a model is not excluded during the statistical evaluation, it means that the observed data does not provide enough evidence to rule it out at the 95% **CL**, making it a viable candidate for further investigation in the search for **SUSY**.

## 7.2.2 General pMSSM Scans

Table no. 7.3 shows the parameter ranges for the **pMSSM** model scan called the General **pMSSM** scan. In this scan, a wide range of processes involving both strong and **EW** interactions are considered. The scan includes mixed production processes from both sectors, such as the production of gluinos and squarks alongside **EWkinos**. For example, it examines gluinos decaying into neutralinos, charginos, and third-generation squarks, ensuring a thorough exploration of mixed production mechanisms. Furthermore, decays of **SM** particles into **SUSY** particles are comprehensively explored, including processes like Higgs boson decays to neutralinos ( $h \rightarrow \chi_1^0 \chi_1^0$ ). The scan also incorporates the associated production of both **SM** and **SUSY** particles. The branching ratios for numerous decay channels, covering both strong and **EW** processes, are calculated, alongside total cross-sections for different production mechanisms. Due to the strong exclusion capabilities of the **ATLAS** experiment for  $\tilde{g}$  and  $\tilde{q}$ , the upper limits for the  $\tilde{g}$  mass parameter  $M_3$  and the left- and right-handed squark mass parameters  $m_{\tilde{q}_i}$  and  $m_{\tilde{u}_i/\tilde{d}_i}$  are set to 5 TeV. Since  $\tilde{g}$  or  $\tilde{q}$  can decay into  $\tilde{\ell}$  through intermediate **EWkinos**, the upper limits for the left- and right-handed slepton mass parameters  $m_{\tilde{\ell}_i}$ ,  $m_{\tilde{e}_i}$  are also scanned up to 5 TeV. The upper limits for the Bino mass parameter  $M_1$ , Wino mass parameter  $M_2$ , and the Higgsino mass parameter  $\mu$  are set to be up to 5 TeV, the trilinear coupling constants' are set to a range up to 8 TeV. In the Higgs sector, the pseudoscalar Higgs boson mass parameter  $M_A$  is set to a range up to 5 TeV, and the vacuum expectation value ratio  $\tan \beta$  is set to a common range of 1 to 60.

Table no. 7.4 shows the number of signal points selected after each step of the General scan's selection process. The General scan initially sampled 1 million signal points, ultimately meeting the **MSSM** model requirements with the **LSP** being  $\tilde{\chi}_1^0$ . The early-stage efficiency of the process was lower than expected, primarily due to infrastructural limitations that restricted the execution to only viable models during critical stages. To address this, we applied a cut on the Higgs boson mass, selecting only models with a mass greater than 100 GeV. This approach was chosen because we intended to impose a more stringent Higgs mass window (mentioned in Table 7.4) later in the procedure, making it reasonable to exclude specific models from the outset. However, this strategy likely reduced the efficiency, limiting it to approximately 13% for further analysis.

Only about 75000 models remain after imposing the  $m(h)$  constraint. This is mainly because the sample adopted in this analysis leads to a relatively low contribution to the Higgs mass for  $\tilde{t}$ . Due to the upper limit of the mass parameter  $M_A$  being 5 TeV, in most models,  $m(A)$  is

| Parameter                            | min    | max   | Note                                                 |
|--------------------------------------|--------|-------|------------------------------------------------------|
| $m_{\tilde{L}_1} (=m_{\tilde{L}_2})$ | 0 TeV  | 5 TeV | Left-handed slepton (first two gens.) mass           |
| $m_{\tilde{e}_1} (=m_{\tilde{e}_2})$ | 0 TeV  | 5 TeV | Right-handed slepton (first two gens.) mass          |
| $m_{\tilde{L}_3}$                    | 0 TeV  | 5 TeV | Left-handed stau doublet mass                        |
| $m_{\tilde{e}_3}$                    | 0 TeV  | 5 TeV | Right-handed stau mass                               |
| $m_{\tilde{Q}_1} (=m_{\tilde{Q}_2})$ | 0 TeV  | 5 TeV | Left-handed squark (first two gens.) mass            |
| $m_{\tilde{u}_1} (=m_{\tilde{u}_2})$ | 0 TeV  | 5 TeV | Right-handed up-type squark (first two gens.) mass   |
| $m_{\tilde{d}_1} (=m_{\tilde{d}_2})$ | 0 TeV  | 5 TeV | Right-handed down-type squark (first two gens.) mass |
| $m_{\tilde{Q}_3}$                    | 0 TeV  | 5 TeV | Left-handed squark (third gen.) mass                 |
| $m_{\tilde{u}_3}$                    | 0 TeV  | 5 TeV | Right-handed top squark mass                         |
| $m_{\tilde{d}_3}$                    | 0 TeV  | 5 TeV | Right-handed bottom squark mass                      |
| $M_1$                                | -5 TeV | 5 TeV | Bino mass parameter                                  |
| $M_2$                                | -5 TeV | 5 TeV | Wino mass parameter                                  |
| $\mu$                                | -5 TeV | 5 TeV | Bilinear Higgs mass parameter                        |
| $M_3$                                | 0 TeV  | 5 TeV | Gluino mass parameter                                |
| $A_t$                                | -8 TeV | 8 TeV | Trilinear top coupling                               |
| $A_b$                                | -8 TeV | 8 TeV | Trilinear bottom coupling                            |
| $A_\tau$                             | -8 TeV | 8 TeV | Trilinear $\tau$ lepton coupling                     |
| $M_A$                                | 0 TeV  | 5 TeV | Pseudoscalar Higgs boson mass                        |
| $\tan \beta$                         | 1      | 60    | Ratio of the Higgs vacuum expectation values         |

Table 7.3: Parameter ranges which are randomly sampled for the General scan.

| Scan name                                  | General            |            |
|--------------------------------------------|--------------------|------------|
| LSP type                                   | $\tilde{\chi}_1^0$ |            |
| <b>Models Generation</b>                   |                    |            |
| Sampled                                    | 1000,000           |            |
| Successful generation                      | 127,247            |            |
| $\tilde{\chi}_1^0$ is the LSP              | 107,506            |            |
| <b>Selection Criteria</b>                  | Strong Prod.       | EWK. Prod. |
| Pass pre-filter                            | 98,052             | 86,158     |
| Successful particle-level evaluation       | 98,045             | 86,141     |
| <b>Selection Criteria</b>                  |                    |            |
| Satisfy LEP and D0 constraint              | 105,283            |            |
| $120 \text{ GeV} < m(h) < 130 \text{ GeV}$ | 75,408             |            |
| Satisfy non-DM external constraints        | 40,212             |            |
| Satisfy all external constraints           | 22,005             |            |

Table 7.4: Set-ups for the pMSSM General Scan and Models Passing Each Step.

far higher than  $m(Z)$ . At this point, under the precision of the one-loop diagram, the mass contribution of  $\tilde{t}$  to the Higgs can be represented as [180]:

$$m(h)^2 = m(h)_{\text{tree}}^2 + \Delta m(h)_{1\text{-loop}}^2$$

Where the one-loop contribution is given by [180]:

$$\Delta m(h)_{1\text{-loop}}^2 = \frac{3m(t)^2}{4\pi^2 v^2} \left( \log \frac{M_S^2}{m(t)^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right)$$

Where,  $X_t = A_t - \mu \cot \beta$  is the  $\tilde{t}$  mixing parameter, and  $M_S = \sqrt{m(\tilde{t}_1)m(\tilde{t}_2)}$  is the **SUSY** scale.

Under one-loop precision, the loop contribution to  $m(h)$  is largest when  $|X_t/M_S| \approx \sqrt{6}$ . However, in a relatively large proportion of the analyzed **pMSSM** models, the ratio  $\frac{X_t}{M_S}$  is less than 1.

After applying non-**DM** constraints, about 40,000 models survive. Most of the other models are excluded by the  $B(b \rightarrow s\gamma)$  constraint due to the upper limit on  $\tan \beta$  in the scan, which is relatively high, and  $\tan \beta$  value significantly impacts  $B(b \rightarrow s\gamma)$  [181]. Finally, after the scan had satisfied all the external constraints, we left with about 22,000 models.

## 7.3 Run 2 ATLAS supersymmetric searches used for Interpretation

---

This analysis uses results from **ATLAS** searches for **SUSY** particles and **BSM** Higgs physics. Table 7.5 summarises the **ATLAS** constraints. The first part targets **SUSY** particles produced via **EW** processes, and the second part targets **SUSY** particles produced via strong processes. These studies focus on simplified models with specific final states.

For the “Disappearing Track” analysis, due to the high precision required for detector simulation, the standard smearing procedure, often used in other analyses, is not suitable in this case this analysis. Hence the exclusion is determined based on whether the production cross-section, mass, and lifetime of  $\tilde{\chi}_1^\pm$  are within the exclusion limits.

For the interpretation of **SUSY** Higgs searches, the first constraint comes from the branching ratio of the Higgs boson decaying to undetectable particles, with a direct constraint on  $B(h \rightarrow \nu\nu) + B(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 0.107$  [194]. The second constraint is related to the theoretical mass limit of the pseudoscalar Higgs boson, with a lower bound set at 480 GeV [195]. The final

| Analysis Name                                           | Example of target SUSY Simplified Model                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|---------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| FullHad [182]                                           | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Wino$ )<br>$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow Wh + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Wino$ )<br>$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow WW + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \approx Wino$ )<br>Higgsino GGM |
| 1Lbb [183]                                              | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow Wh + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Wino$ )                                                                                                                                                                                                                                                                                                                                                         |
| 2L0J [184]                                              | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow WW + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \approx Wino$ )<br>$pp \rightarrow \tilde{\ell} \tilde{\ell} \rightarrow \ell \ell + \tilde{\chi}_1^0 \tilde{\chi}_1^0$                                                                                                                                                                                                                                             |
| 2L2J [185]                                              | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Wino$ )<br>Higgsino GGM                                                                                                                                                                                                                                                                                                                                         |
| 3L [186]                                                | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Wino, \tilde{\chi}_1^0 \approx Bino$ )<br>$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow Wh + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Higgsino$ )<br>Higgsino GGM                                                                                                                                    |
| 4L [187]                                                | Higgsino GGM                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| Compressed [188]                                        | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow WZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \approx Higgsino$ )                                                                                                                                                                                                                                                                                                                                                     |
| Disappearing Track [189]                                | $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0 j \rightarrow \pi^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 j$ ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \approx Wino/Higgsino$ )                                                                                                                                                                                                                                                                                                                                         |
| Strong 1L [190]                                         | $pp \rightarrow \tilde{q} \tilde{q} \rightarrow q \tilde{\chi}_1^\pm q \tilde{\chi}_1^\pm \rightarrow qqWW + \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ( $\tilde{\chi}_1^\pm \approx Wino, \tilde{\chi}_1^0 \approx Bino$ )                                                                                                                                                                                                                                                                                                   |
| Strong 2L2J [185]                                       | $pp \rightarrow \tilde{g} \tilde{g} / \tilde{q} \tilde{q} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow ZZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$<br>$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \ell \tilde{\ell} \nu \tilde{\nu} \rightarrow \ell \ell \nu \nu + \tilde{\chi}_1^0 \tilde{\chi}_1^0$                                                                                                                                                                                      |
| Strong SS/3L [191]                                      | $pp \rightarrow \tilde{g} \tilde{g} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow WW + \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow WWZZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$                                                                                                                                                                                                                                                                                                                         |
| Strong Multijets [192]                                  | $pp \rightarrow \tilde{g} \tilde{g} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow WW + \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow WWZZ + \tilde{\chi}_1^0 \tilde{\chi}_1^0$<br>$pp \rightarrow \tilde{g} \tilde{g} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ directly                                                                                                                                                                                                                          |
| Strong 0L [193]                                         | Multi-bin, BDT, and Discovery analyses<br>$pp \rightarrow \tilde{g} \tilde{g} / \tilde{q} \tilde{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow WW + \tilde{\chi}_1^0 \tilde{\chi}_1^0$<br>$pp \rightarrow \tilde{g} \tilde{g} / \tilde{q} \tilde{q} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ directly                                                                                                                                                                                         |
| $B(h \rightarrow \text{inv})$ measurement [194]         | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| $m(A)$ measurement [195]                                | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| $\sigma_{\phi \rightarrow \tau \tau}$ measurement [196] | -                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |

Table 7.5: List of ATLAS searches considered in this analysis.

constraint is from the cross-section of pseudoscalar Higgs boson decays to  $\tau\tau$ , using the SUSHI [197] framework to calculate production cross-sections and branching ratios, and determining exclusion based on whether the mass and cross-section times branching ratio are within the exclusion limits [196].

## 7.4 Analysis Results

---

This section summarises the analysis results. For simplicity, the following keywords are used in the plots:

- **ATLAS Run 2 searches** includes constraints from both **SUSY** and Higgs studies.
- **ATLAS SUSY (Higgs) searches** includes constraints only from **ATLAS SUSY (Higgs)** studies.
- **EWK (Strong) Prod.** includes constraints from **EW** (strong) processes producing **SUSY** particles.
- **Strong+EWK Prod.** selects the stronger constraint (the smaller **CLs**) between the two.
- **all non-DM constraints** include all non-**ATLAS** constraints except direct detection **DM** experiments as given in Table 7.2.
- **all constraints** includes all non-**ATLAS** constraints as given in Table 7.2.

Because of space limitations, the constraints on 19 **pMSSM** parameters are in Appendix C. The exclusion capabilities for non-**ATLAS** constraints on **pMSSM** models are in Appendix C.

This section will show the constraints on **SUSY** particle masses and decay branching ratios from **ATLAS** and non-**ATLAS** experiments. For these one-dimensional distributions:

- (a) Shows the distribution of all models before and after applying **ATLAS** experimental constraints. The blue dashed line indicates constraints from only the **ATLAS** Higgs studies.
- (b) Shows the distribution of all models after applying constraints from non-**ATLAS** experiments, both with and without **ATLAS** Higgs study constraints and with non-**ATLAS** and **ATLAS** constraints.

### 7.4.1 LSP Mass Constraints

Figure 7.3 shows the mass distribution of the **LSP** and the proportion of models excluded based on different constraints. In Figure 7.3a, we see the mass distribution of all models before and after applying constraints from the **ATLAS** experiment. The blue dashed line represents the constraints related to Higgs's research from the **ATLAS** experiment. In Figure 7.3b, the mass distribution of all models is shown after applying non-**ATLAS** experiment constraints, after applying non-**ATLAS** experiment constraints combined with **ATLAS** Higgs constraints, and after applying both non-**ATLAS** and **ATLAS** experiment constraints (all constraints).

The **ATLAS** experiment constraints mainly affect the low-mass region of the **LSP**. The **ATLAS** experiment excluded 95% of models where the **LSP** mass is below 100 GeV. Additionally, more than 92% of models with an **LSP** mass below 400 GeV are excluded by the **ATLAS** experiment. When non-**ATLAS** experiment constraints are included, 97% of models with a **LSP** mass below 500 GeV are excluded. Furthermore, nearly 95% of the models are excluded by **ATLAS** and non-**ATLAS** experiment constraints almost across the entire range.

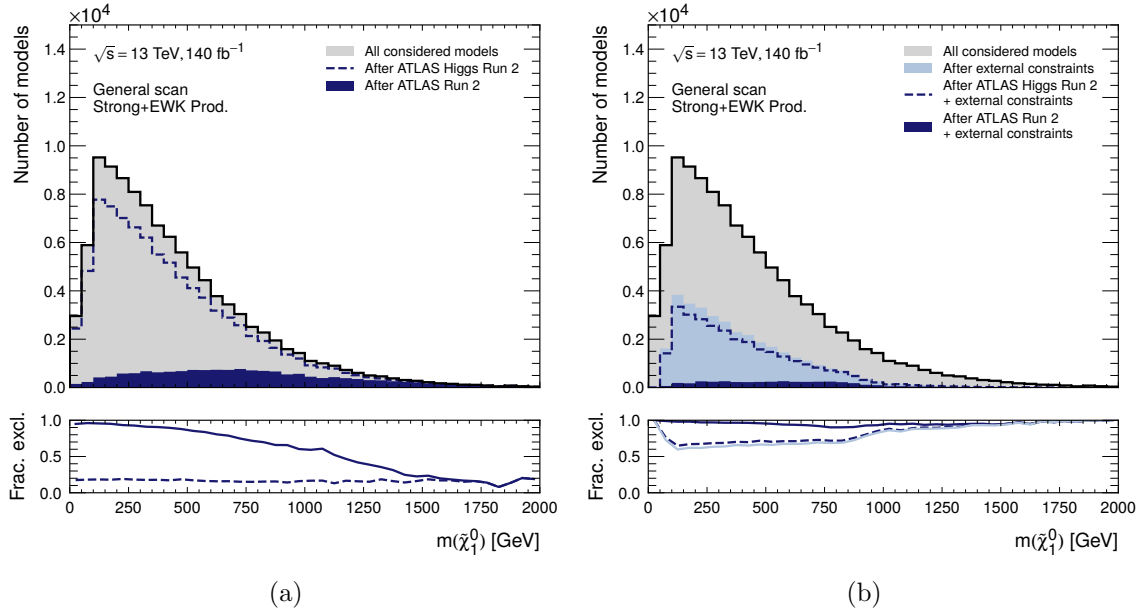


Figure 7.3: Distribution of the LSP mass for the General scan. (a) The distribution of all general models considered, both before and after the application of ATLAS Run 2 constraints, with the blue dashed line indicating the moderately excluded strains applied. (b) The distribution of all General scan models prior to any constraints, the remaining models after applying all external constraints, after applying both external constraints and the ATLAS Higgs Run 2 constraints, and finally after applying all external and ATLAS Run 2 constraints. The lower panels display the fraction of models excluded in each scenario.



### 7.4.2 ATLAS constraints on the strong production side

For the two-dimensional distributions in this section, the bins are color-coded as follows: grey bins contain no models, cream bins contain models that are all excluded, and black bins contain models that are not excluded. Each figure will consist of three plots:

- (a) Including all models.
- (b) Including models constrained by non-**ATLAS** experiments.
- (c) Including models constrained by non-**ATLAS** experiments and **ATLAS** Higgs study constraints.

Figure 7.4 shows the exclusion ratios of the **ATLAS SUSY** study for the General scan models. The first column shows the distribution of  $m(\tilde{g}) - m(\tilde{\chi}_1^0)$ , and the second column shows the distribution of  $m(\tilde{q}) - m(\tilde{\chi}_1^0)$ , where  $\tilde{q}$  represents the first and second generation left-handed and right-handed squarks ( $\min[m(\tilde{q}_L), m(\tilde{q}_R)], q \in \{u, d, c, s\}$ ). The model is also displayed, showing both **ATLAS**-constraints and non-**ATLAS**-constraints models and the exclusion scenarios of the Higgs studies by **ATLAS** models. The **ATLAS** exclusion limit in the figure is based on a simplified model exclusion limit for the related analysis.

It can be observed that the **ATLAS SUSY** study has extremely high exclusion ratios for models with relatively light  $m_{\tilde{g}}$  under different constraints. Meanwhile, the exclusion range for **pMSSM** models is close to that of the simplified model exclusion limits, indicating that the simplified model effectively captures the characteristics of **pMSSM**  $\tilde{g}$  models. The region where  $m(\tilde{g}) \leq 1$  TeV is almost completely excluded. Additionally, some **pMSSM** models are not excluded within the simplified model exclusion limits. These non-excluded models are primarily found in regions where the gluino mass is relatively high ( $m(\tilde{g}) \geq 2000$  GeV) and the mass difference with the **LSP** ( $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ ) is significantly greater than few GeV, often ranging between 500 and 1000 GeV.

Additionally, it can be observed that for  $m(\tilde{g}) \sim 2$  TeV and a relatively low **LSP** mass, the exclusion range for **pMSSM** models exceeds that of the simplified models. This is because when  $\tilde{g}$  is heavy and the mass difference between  $\tilde{g}$  and  $\tilde{\chi}_1^0$  is large, other **SUSY** particles can participate in the  $\tilde{g}$  decay process, forming complex cascades with many low  $p_T$  final states. The **ATLAS SUSY** analysis of strong production processes indicates that even when the mass of the gluino  $m(\tilde{g})$  approaches 4 TeV, nearly 50% of the models are still excluded. This is because the simplified models in this analysis do not decouple  $\tilde{q}$ , and the models with relatively light  $\tilde{q}$  are excluded by **SUSY** analysis, making the models appear excluded in the  $m(\tilde{g}) - m(\tilde{\chi}_1^0)$  plane projection.

In the  $m(\tilde{q}) - m(\tilde{\chi}_1^0)$  plane, the region with  $m(\tilde{q}) \leq 400$  GeV is almost completely excluded. Meanwhile, many models are still excluded when the mass of  $m(\tilde{q}) > 2$  TeV. This is due to the processes involving  $\tilde{g}\tilde{g}$  or  $\tilde{g}\tilde{q}$ . However, the region between the dashed and solid lines

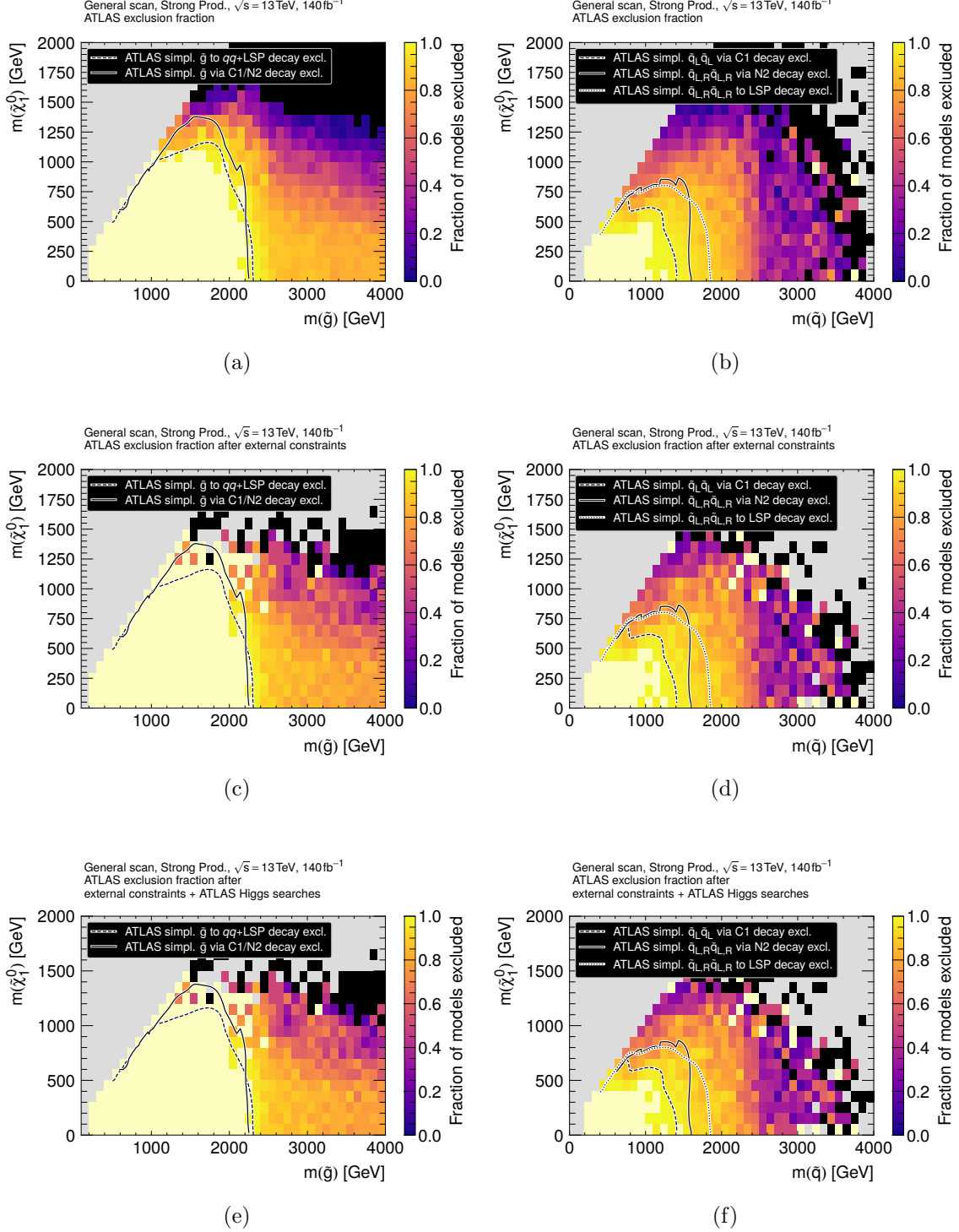


Figure 7.4: Fraction of General scan models excluded by the ATLAS Run 2 SUSY results with Strong production. The first column, (a) (c) (e), shows the  $m(\tilde{g})$  vs.  $m(\tilde{\chi}_1^0)$  plane and the second column, (b) (d) (f), shows the  $m(\tilde{q})$  vs.  $m(\tilde{\chi}_1^0)$  plane. The first row includes all models. The second includes all models that pass all external constraints, and the third-row models pass the external constraints and ATLAS Higgs searches.

(representing the ATLAS Simplified model exclusion limits for different decay channels) is not completely excluded within the simplified model exclusion limits. Specifically, the dashed line corresponds to the exclusion contour for  $\tilde{q}_L \tilde{q}_L$  decaying via a chargino ( $\tilde{\chi}_1^\pm$ ) process, while the solid line represents squark decays via the next-to-lightest neutralino ( $\tilde{\chi}_2^0$ ). The difference in exclusion limits may arise because the simplified models assume different decay modes. The solid line reflects the assumption that  $\tilde{q}_L$  and  $\tilde{q}_R$  have similar masses, while the dashed line considers only  $\tilde{q}_L$ , leading to variations in the exclusion region. In **pMSSM** models, the first and second generations of  $\tilde{q}_L$  share a mass parameter, making the exclusion behaviour more complex when different decay modes are considered.

Figure 7.5 shows the exclusion ratio of the **ATLAS SUSY** experiment projected onto the  $m(\tilde{g}) - m(\tilde{q})$  plane, considering the simplified model exclusion limit for the octet of  $\tilde{q}$  and the  $\tilde{g}\tilde{q}$  production process. It can be seen that the region where the mass of  $\tilde{g}$  is lower than 1

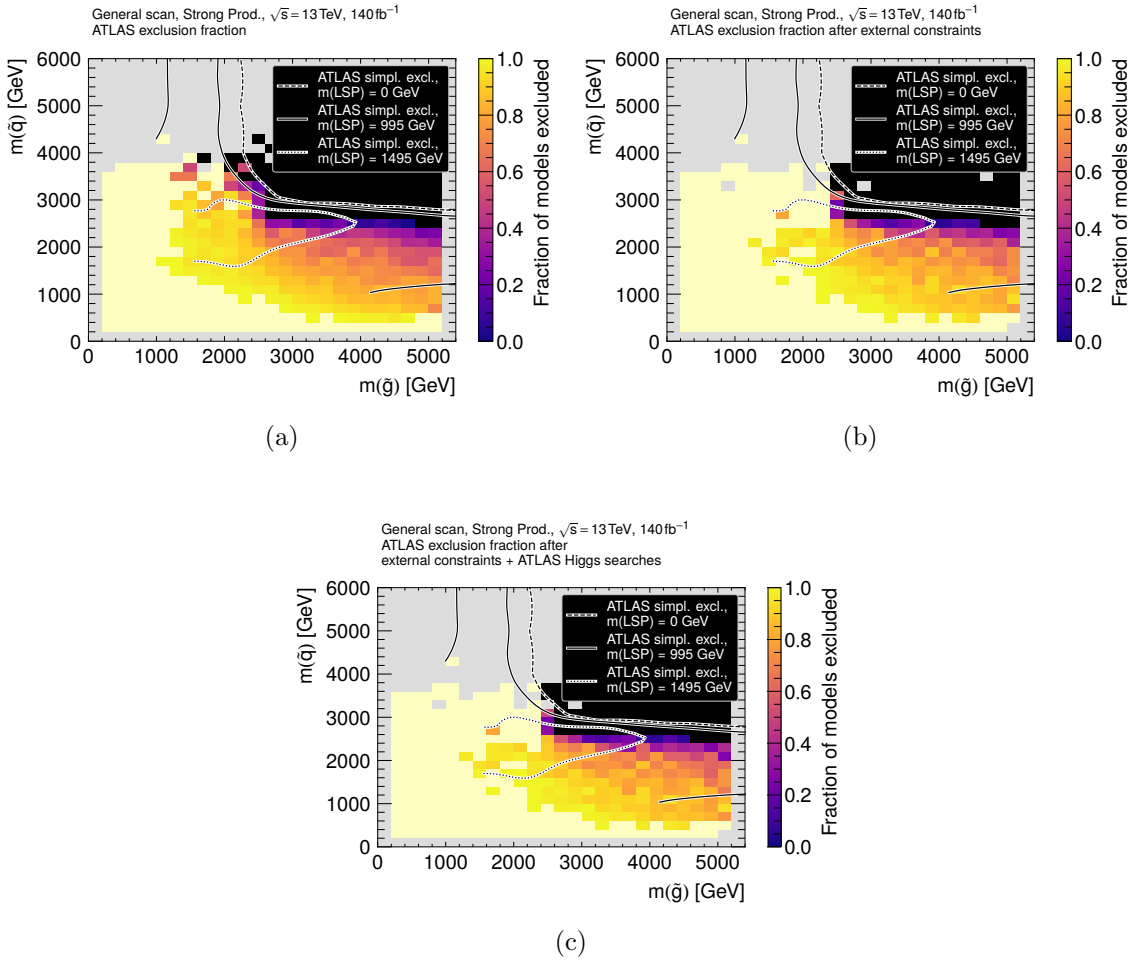


Figure 7.5: Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. Figure(a) shows the  $m(\tilde{g})$  vs.  $m(\tilde{q})$  plane includes all models, (b) includes all models that pass all external constraints, and (c) includes models that pass the external constraints and ATLAS Higgs searches.

TeV is completely excluded, and the exclusion capability is independent of the mass of  $\tilde{q}$ . At the same time, the lighter  $\tilde{q}$  is strongly constrained by the **ATLAS SUSY** study due to the higher production cross-section of  $\tilde{g}\tilde{q}$  pairs at low masses. When the mass of ( $\tilde{g}$ ) is low,  $\tilde{q}$  with masses under 1 TeV are fully excluded because of the experiment's increased sensitivity to these low-mass particles.

Some **pMSSM** models outside the simplified model exclusion limits are also excluded, particularly those with relatively light **LSP** masses. In these models, the masses of squarks ( $\tilde{q}$ ), stops ( $\tilde{t}$ ), and sbottoms ( $\tilde{b}$ ) are close, leading to stronger interactions between these particles. This increases the likelihood of their production in experiments, making it easier for the experiment to detect and exclude these models. As a result, regions where the  $\tilde{g}$  and  $\tilde{q}$  masses are close show a high proportion of excluded **pMSSM** models due to the higher cross-section of the  $\tilde{g}\tilde{q}$  production process in these areas.

Figure 7.6 separately shows the exclusion limits of  $\tilde{q}_L$  and  $\tilde{q}_R$ . By comparing the two columns on the left and right, it can be seen that the exclusion power is stronger for  $\tilde{q}_L$  compared to  $\tilde{q}_R$ . This shows that the  $\tilde{q}_L$  plays a more significant role in driving the exclusion of  $\tilde{q}$  in figure 7.4. In the **pMSSM** model, the first and second-generation squarks share a common mass parameter, making their masses theoretically very close. This creates a situation where the left-handed squarks  $\tilde{q}_L$  from the first and second generations have nearly the same mass. Because of this mass similarity, the exclusion sensitivity for  $\tilde{q}_L$  is enhanced, meaning it is easier to rule out or detect. On the other hand, the right-handed squarks,  $\tilde{q}_R$ , do not experience the same level of degeneracy, which results in a weaker exclusion sensitivity for them.

The **SUSY** simplified model often uses fixed branching ratios, such as setting the branching ratio of a **SUSY** particle decay to a specific value of 100%. However, in the **pMSSM** model, the branching ratios vary with different model parameters. Figure 7.7 shows the branching ratios of  $\tilde{g}$  decaying to **EWkino** ( $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ , and  $\tilde{\chi}_1^\pm$ ),  $\tilde{q}_L$ ,  $\tilde{q}_R$ , and  $\tilde{t}/\tilde{b}$ . Overall, the exclusion ratios of the **ATLAS** experimental **SUSY** study are generally high across all branching ratio distributions, some variations in the exclusion ratios with changing branching ratios can still be observed. When the branching ratio of  $\tilde{g}$  decaying to **EWkino** is high, the exclusion ratio of the **ATLAS** analysis is also high. This is because **SUSY** analysis often selects simplified models where the decay to **EWkino** serves as the signal model, thus enhancing the exclusion capability for models with high branching ratios of decays to **EWkino** in the **SUSY** model. Additionally, the exclusion ratio increases with decreasing  $B(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$  or increasing  $B(\tilde{g} \rightarrow \tilde{q}_L/\tilde{q}_R)$ . This is mainly because the **pMSSM** general scan analysis has not yet focused on the third-generation squark analysis, making the exclusion capability for high  $B(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$  weaker, and these two

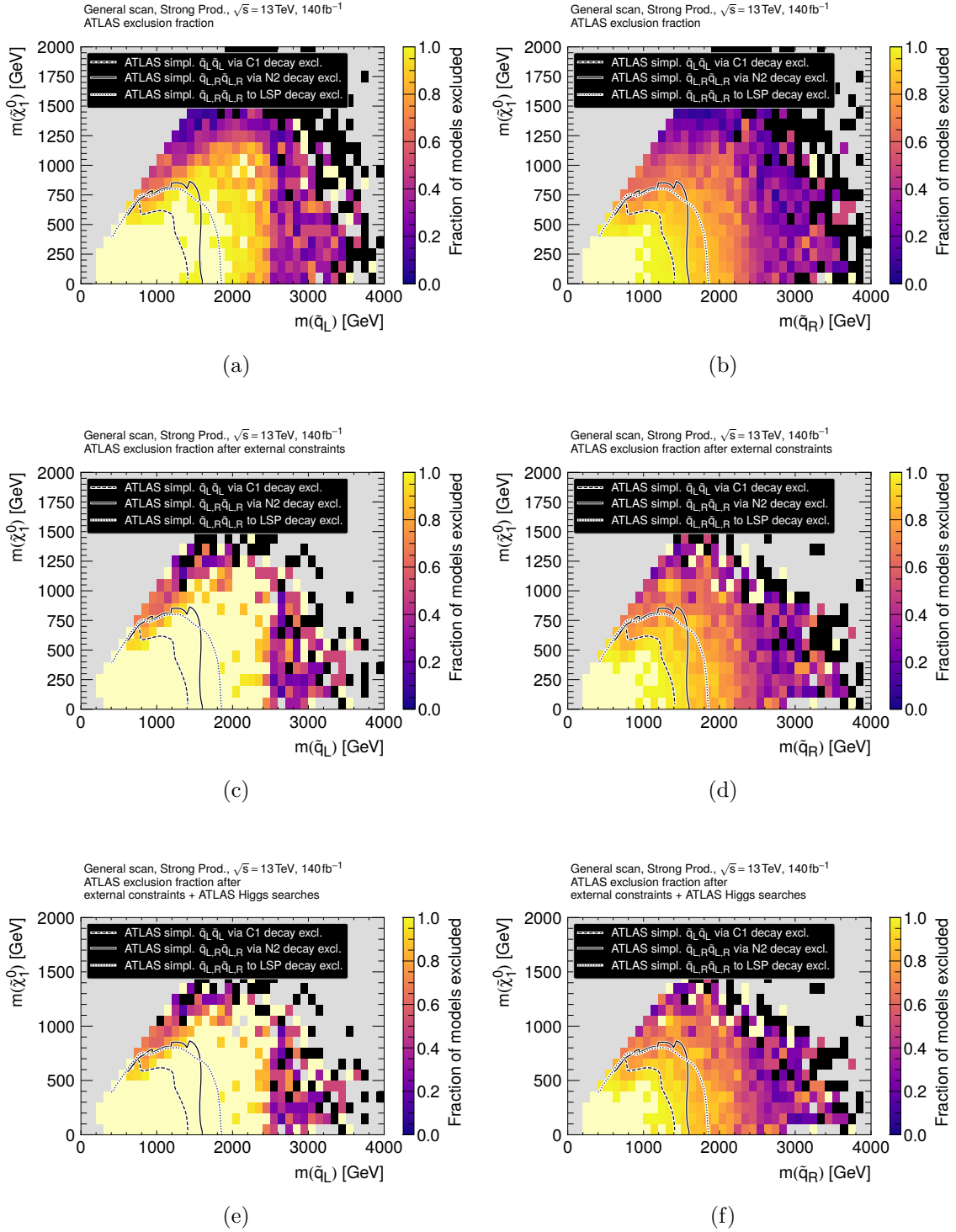


Figure 7.6: Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. The first column, (a) (c) (e), shows the  $m(\tilde{q}_L)$  vs.  $m(\tilde{\chi}_1^0)$  plane and the second column, (b) (d) (f), shows the  $m(\tilde{q}_R)$  vs.  $m(\tilde{\chi}_1^0)$  plane. The first row includes all models, the second includes all models that pass all external constraints and the third row models that pass the external constraints and ATLAS Higgs searches. (a), (c), and (e) only consider the models with the first two generations of left-handed squark as the lightest squark. (b), (d), and (f) only consider the models with the first two generations of right-handed squark as the lightest squark.

branching ratios are in a “competitive” relationship. Figures 7.8 and 7.9 separately show the exclusion ratio and the relationship between the branching ratios of  $\tilde{q}_L$  and  $\tilde{q}_R$ . Among them, the branching ratio  $B(\tilde{q}_L \rightarrow \tilde{\chi}_2^0)$  endpoint is consistent with the reasons for the cutoff points in the  $\tilde{g}$  branching ratios. Overall, all the branching ratios have high exclusion fractions.

### The Mass Constraints of the Third Generation of Superpartners

In **SUSY** models, third-generation squarks ( $\tilde{t}, \tilde{b}$ ) are often considered lighter than other squarks, particularly because a lighter stop ( $\tilde{t}$ ) can solve the naturalness problem. Figure 7.10 shows the mass exclusion ratios of  $\tilde{t}$  and  $\tilde{b}$ , using the **SUSY** model where the lightest squark is  $\tilde{t}$  or  $\tilde{b}$ . The simplified model exclusion limits still come from searches targeting first- and second-generation  $\tilde{q}$  in the **ATLAS** analysis. However, in many cases involving the third-generation squarks ( $\tilde{t}$  and  $\tilde{b}$ ), the masses of particles like the stop ( $\tilde{t}$ ) and the neutralino are not similar, meaning they do not have “degenerate” masses. This lack of mass similarity results in exclusion regions for third-generation squarks that differ from those of first- and second-generation squarks. Since this **pMSSM** analysis did not consider the third-generation squark analysis, the exclusion ratio for **SUSY** is relatively low. Even so, it can be seen that  $\tilde{t}$  or  $\tilde{b}$  with a mass less than 600 GeV is almost completely excluded.

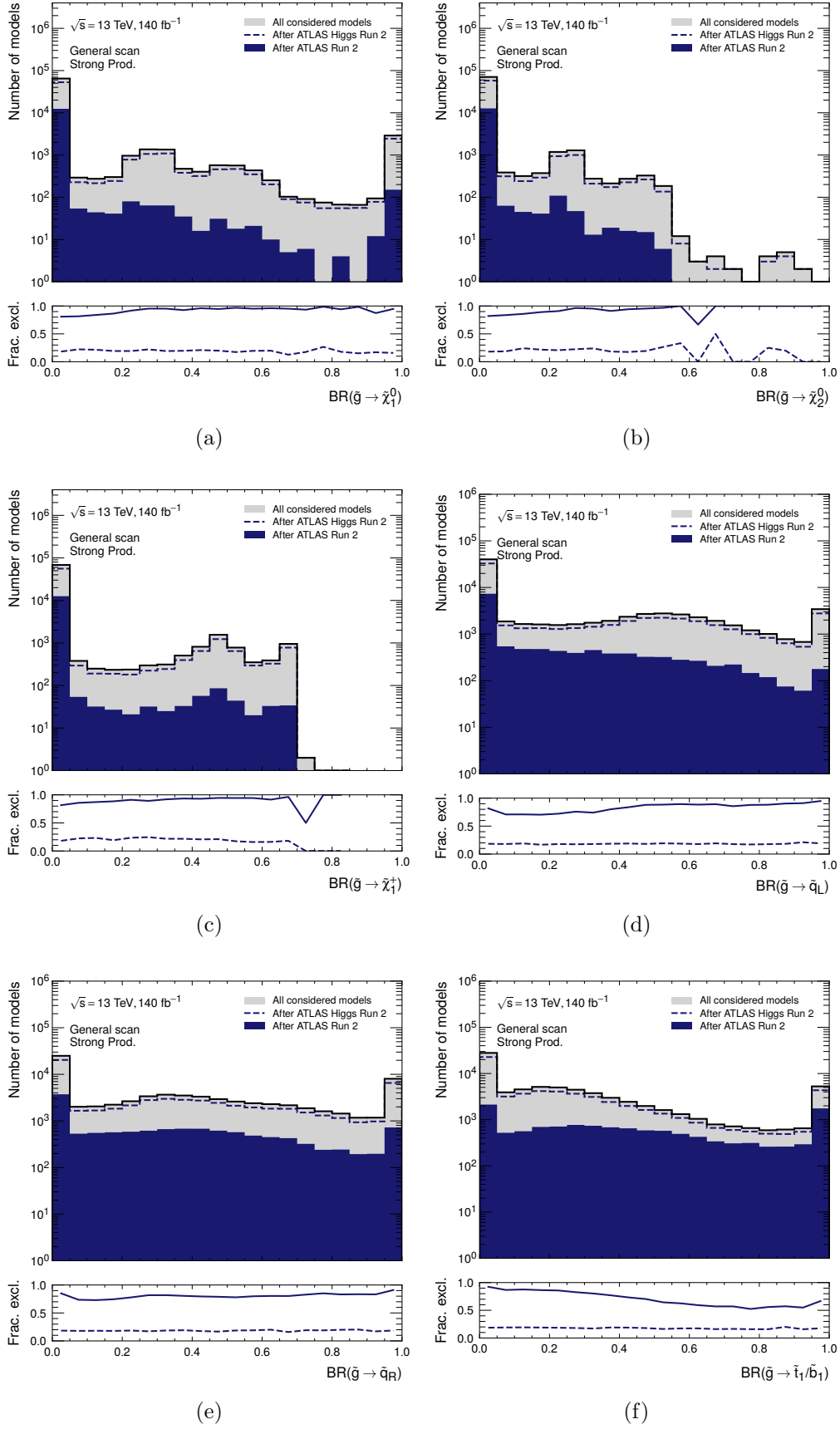


Figure 7.7: Distribution of branching ratios (BR) for various decay modes of  $\tilde{g}$  in the pMSSM General Scan.

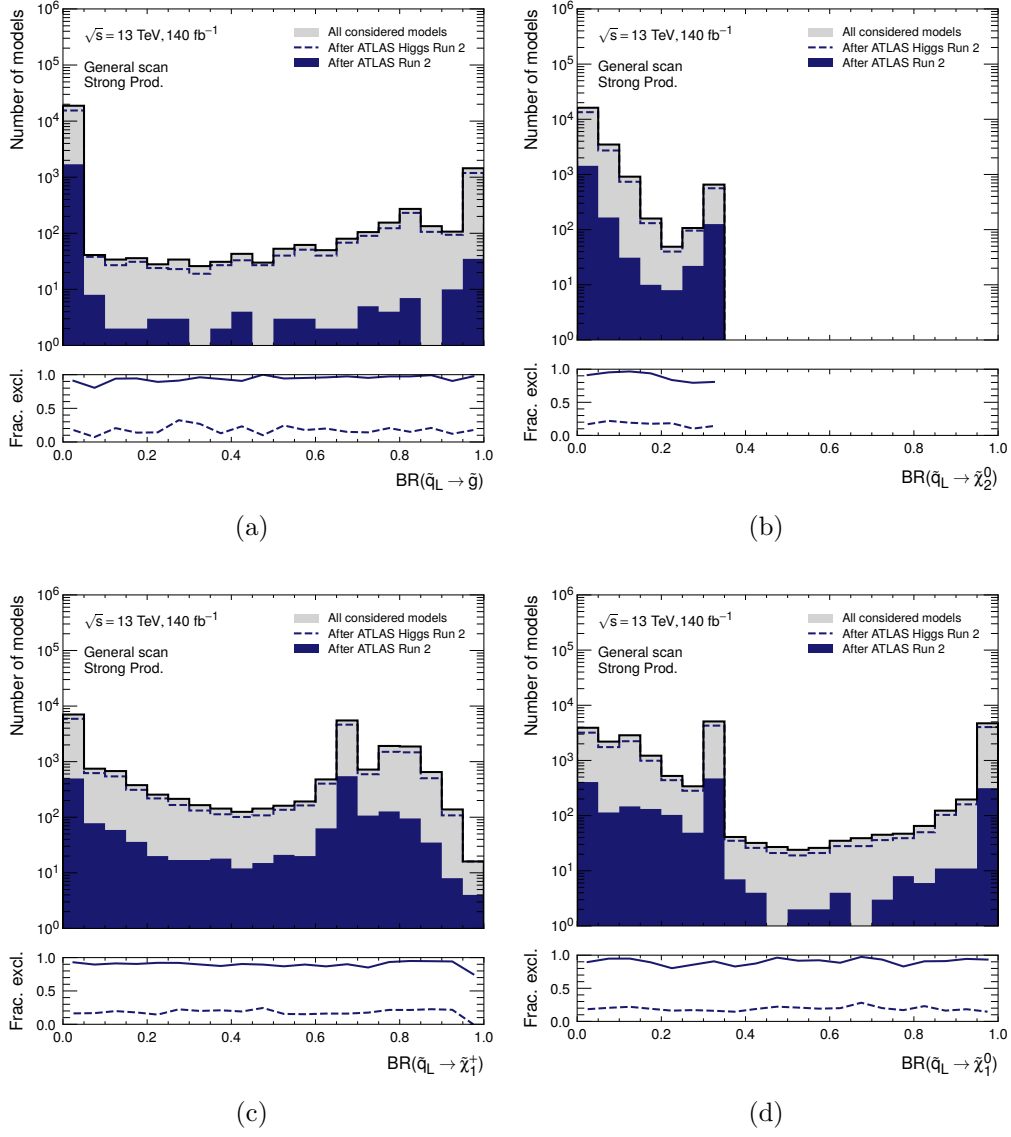


Figure 7.8: Distribution of branching ratios (BR) for various decay modes of  $\tilde{q}_L$  in the pMSSM General Scan.



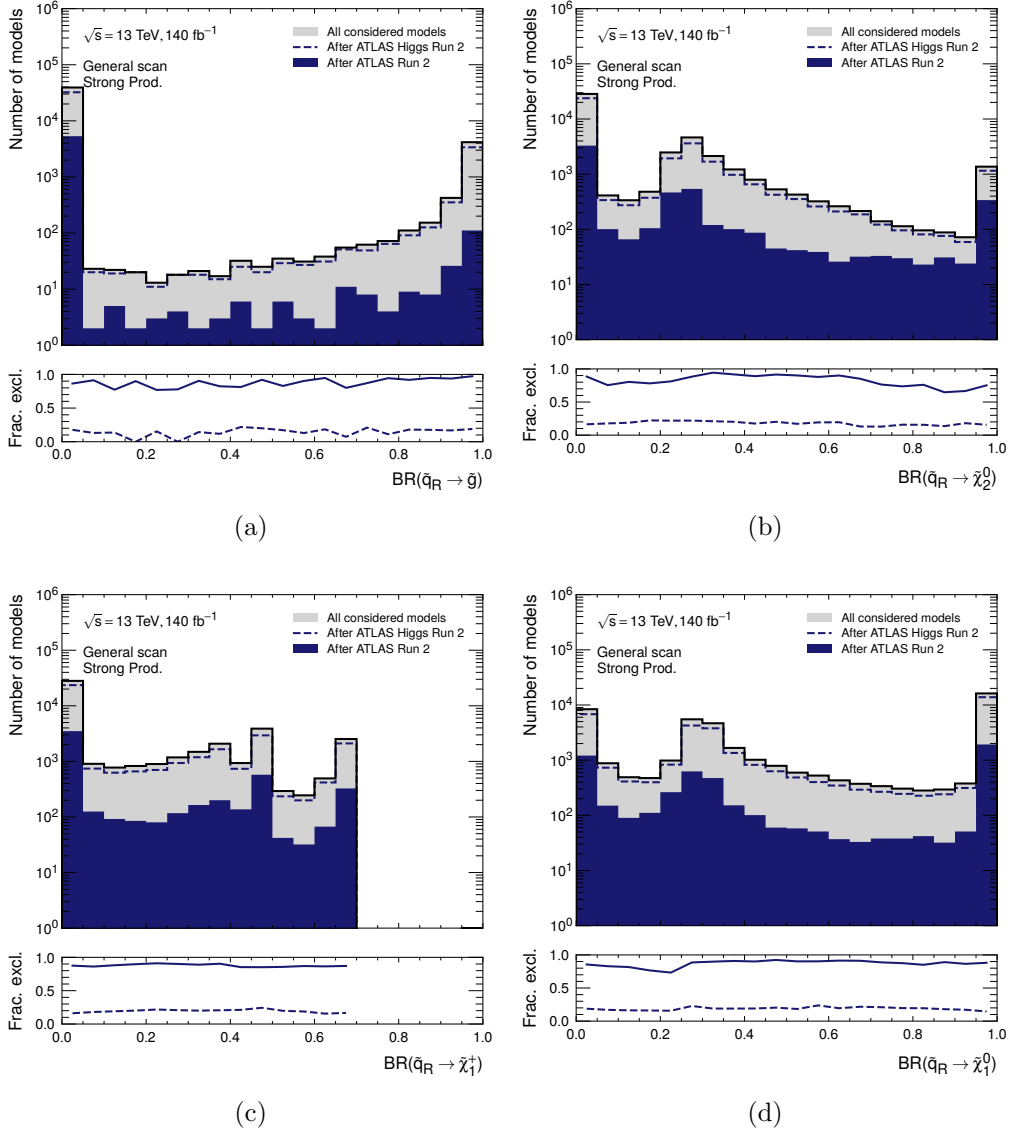


Figure 7.9: Distribution of branching ratios (BR) for various decay modes of  $\tilde{q}_R$  in the pMSSM General Scan.

### 7.4.3 ATLAS constraints on the electroweak production side

This section will focus mainly on the **ATLAS** constraints on supersymmetric **EW** gauges and first to third-generation supersymmetric leptons. Figure 7.11 shows the exclusion limits of the **ATLAS SUSY** study for the pMSSM model projected onto the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  versus **LSP** ( $\tilde{\chi}_1^0$ ) mass plane in the **EWkino** sector. Considering that **EWkinos** can be involved in the decay of strongly produced  $\tilde{g}$  or  $\tilde{q}$ , the best exclusion **CL** between strong and **EW** production is used to determine if the model is excluded when **EWkinos** are involved in the decay. The exclusion limits for simplified models in the figure come from relevant **SUSY** analyses targeting **EW** processes. The region with  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  masses below 300 GeV is almost excluded. If the **LSP** mass is relatively low, the **ATLAS** experiment's constraints on the pMSSM can reach the

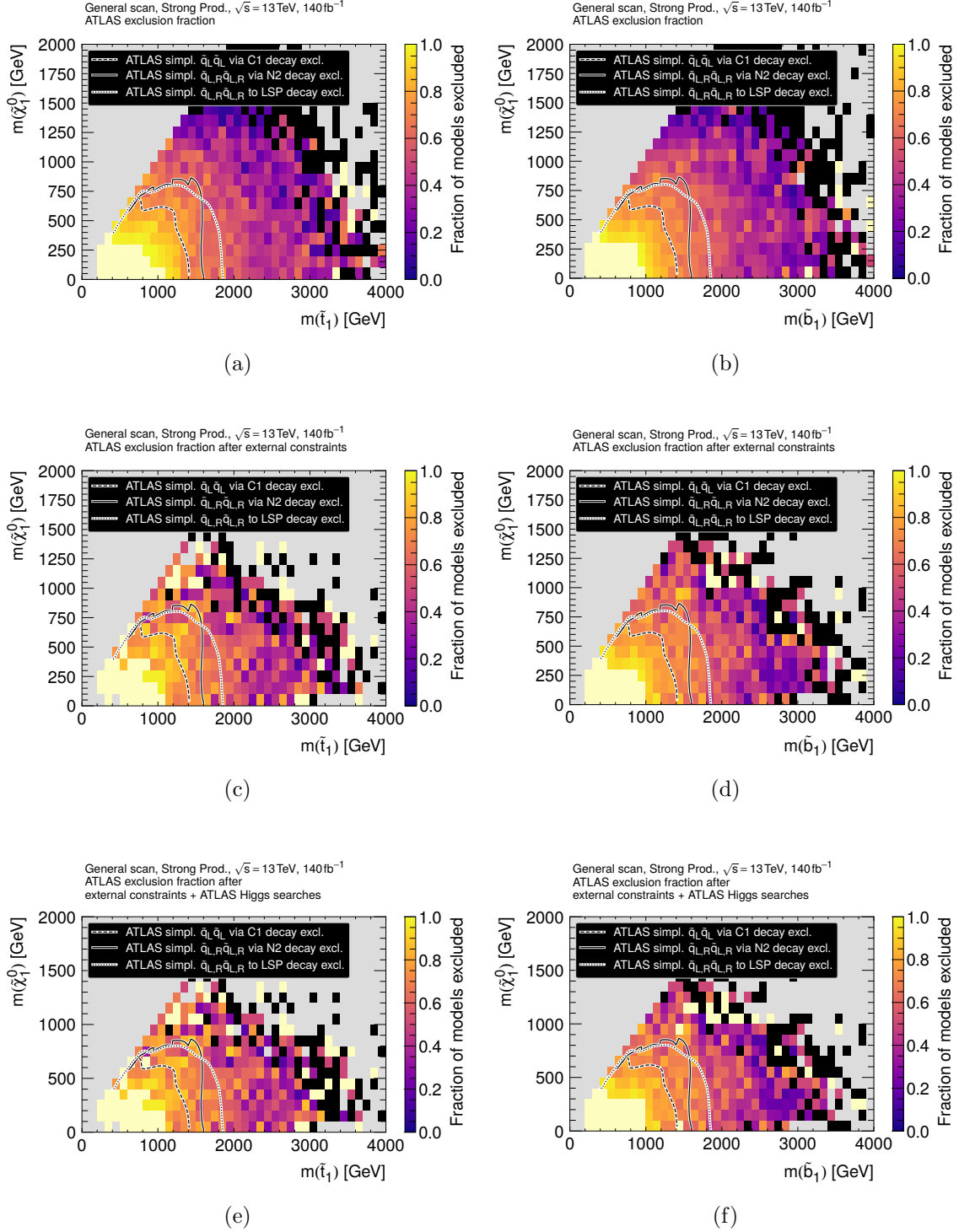


Figure 7.10: Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. The first column, (a) (c) (e), shows the  $m(\tilde{t})$  vs.  $m(\tilde{\chi}_1^0)$  plane, and the second column, (b) (d) (f), shows the  $m(\tilde{b})$  vs.  $m(\tilde{\chi}_1^0)$  plane. The first row includes all models. The second includes all models that pass all external constraints, and the third-row models pass the external constraints and ATLAS Higgs searches.

TeV scale, mainly due to decays through  $\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0$  involving  $\tilde{g}$  or  $\tilde{q}$ . In contrast, it can be seen that many bins in the exclusion limits of simplified models have exclusion percentages far below 100%, mainly because the exclusion limits of simplified models often assume a 100% branching ratio, while in the **pMSSM** model, there are multiple decay channels for  $\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0$ .

Additionally, figures 7.11c and 7.11d show that after the external constraints, we are left with very few models (especially in the case of  $\tilde{\chi}_1^\pm$ ) which means these external constraints are very strong in case of **EWkinos** exclusion fractions. These figures also show a mass region in the (nearly) compressed mass where the exclusion percentages of the **pMSSM** models are higher and beyond the simplified model exclusion limits. In the extremely compressed mass region, the exclusion percentage is close to 80%, primarily due to the disappearing-track analysis and the production of higher-mass **EWkinos**, such as  $\tilde{\chi}_2^\pm$  or  $\tilde{\chi}_4^0$ . In this region, the  $\tilde{\chi}_1^\pm$  has a longer lifetime and can leave a track segment before decaying, where the decay product  $\tilde{\chi}_1^0$  does not produce track information, resulting in a signal end state that appears as a suddenly disappearing track. Thus, the disappearing-track analysis is sensitive to signals in the compressed mass region.

Figure 7.12 shows the projection of exclusion limits in the branching ratio distribution of  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$ . It can be observed that the **ATLAS SUSY** experimental constraints are strong in all three cases.

Figure 7.13 shows the exclusion fractions of the **ATLAS SUSY** analysis projected onto the mass plane of the first and second-generation supersymmetric sleptons  $\tilde{\ell}$  and the third-generation supersymmetric slepton  $\tilde{\tau}$  versus the **LSP** mass. The simplified model on the figures considers the left and right-handed  $\tilde{l}$  of the first and second generations.

In the **pMSSM** model, the **EWkinos** are not decoupled from the  $\tilde{\ell}$  or  $\tilde{\tau}$ , meaning that processes involving **EWkinos** production contribute significantly to the exclusion. **EWkinos** production tends to have higher cross-sections, meaning these processes occur more frequently than direct  $\tilde{\ell}$  or  $\tilde{\tau}$  production. As a result, even though the simplified model mainly focuses on direct slepton production, the **pMSSM** model shows that constraints on  $\tilde{\ell}$  are broader due to the influence of **EWkinos** production. This expands the exclusion limits compared to those in the simplified model.

There are also some regions within the exclusion limits of the simplified model where the **pMSSM** model is not excluded. The reason is that the left and right-handed  $\tilde{l}$  mass parameters differ in the **pMSSM** model, and the left-handed  $\tilde{l}$  has a higher mass in the model. Additionally, the exclusion fraction of  $\tilde{l}$  is much higher than that of  $\tilde{\tau}$  mainly because the analysis targeting  $\tilde{\tau}$  was not considered in this analysis, and the proportion of leptons produced by the decay of

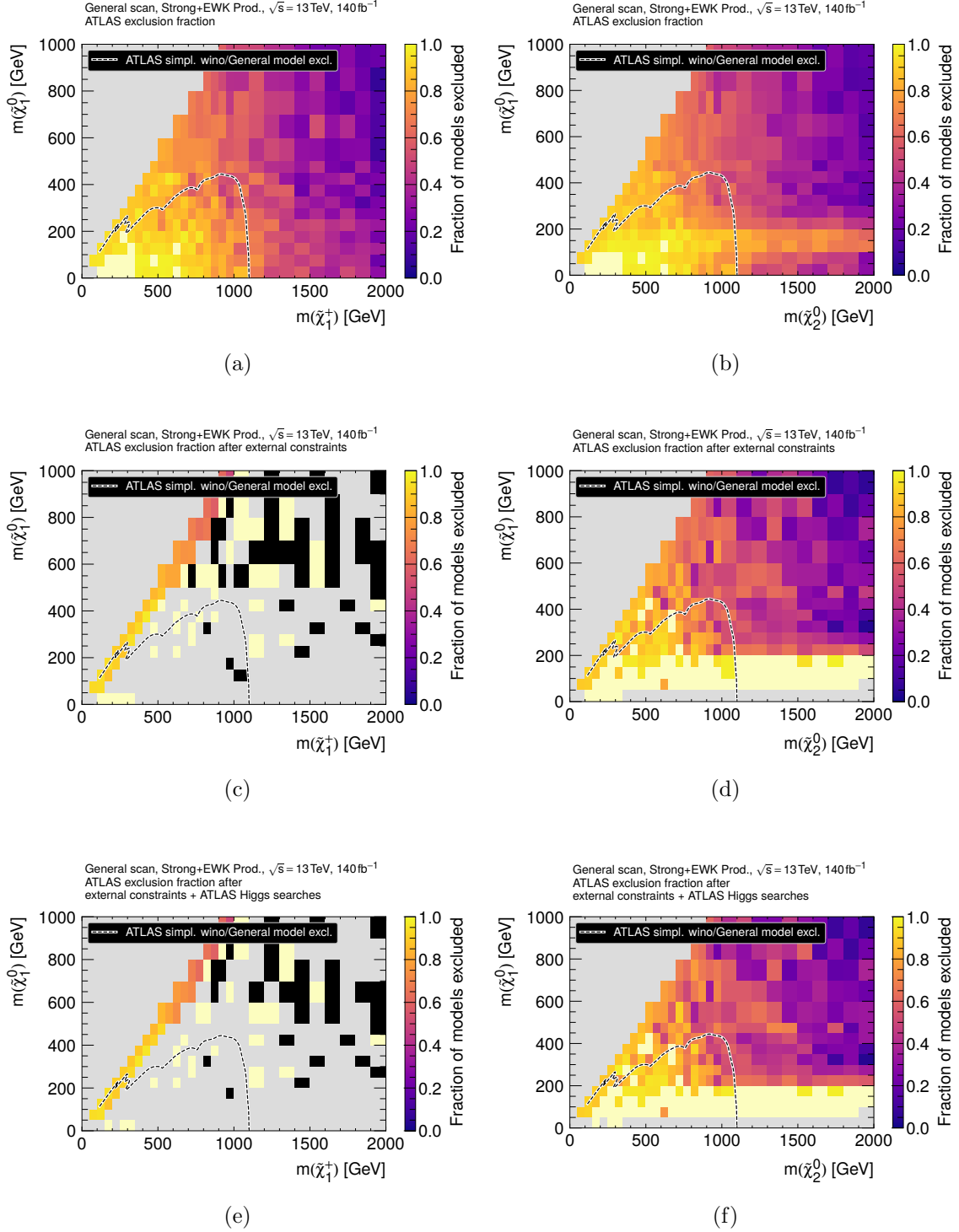
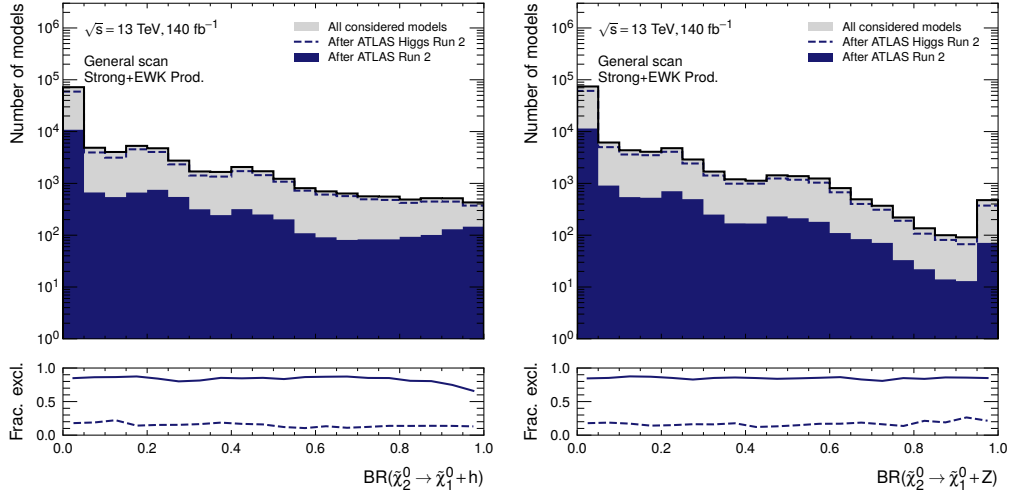
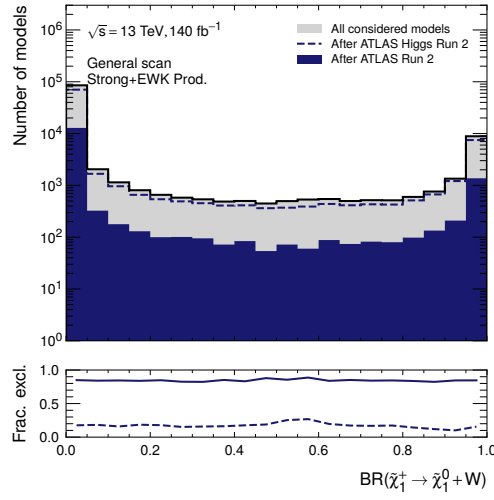


Figure 7.11: The proportion of General scan models excluded by ATLAS SUSY results. The first column presents the  $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$  plane, while the second column displays the  $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$  plane. The top row shows all considered models, the second row shows models that satisfy all external constraints, and the third row depicts models that satisfy both external and ATLAS Higgs constraints.



(a)

(b)



(c)

Figure 7.12: Distributions of  $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h)$ ,  $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z)$  and  $\text{BR}(\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W)$  in the pMSSM General scan.

$\tilde{l}$  is relatively higher compared to  $\tilde{\tau}$ .

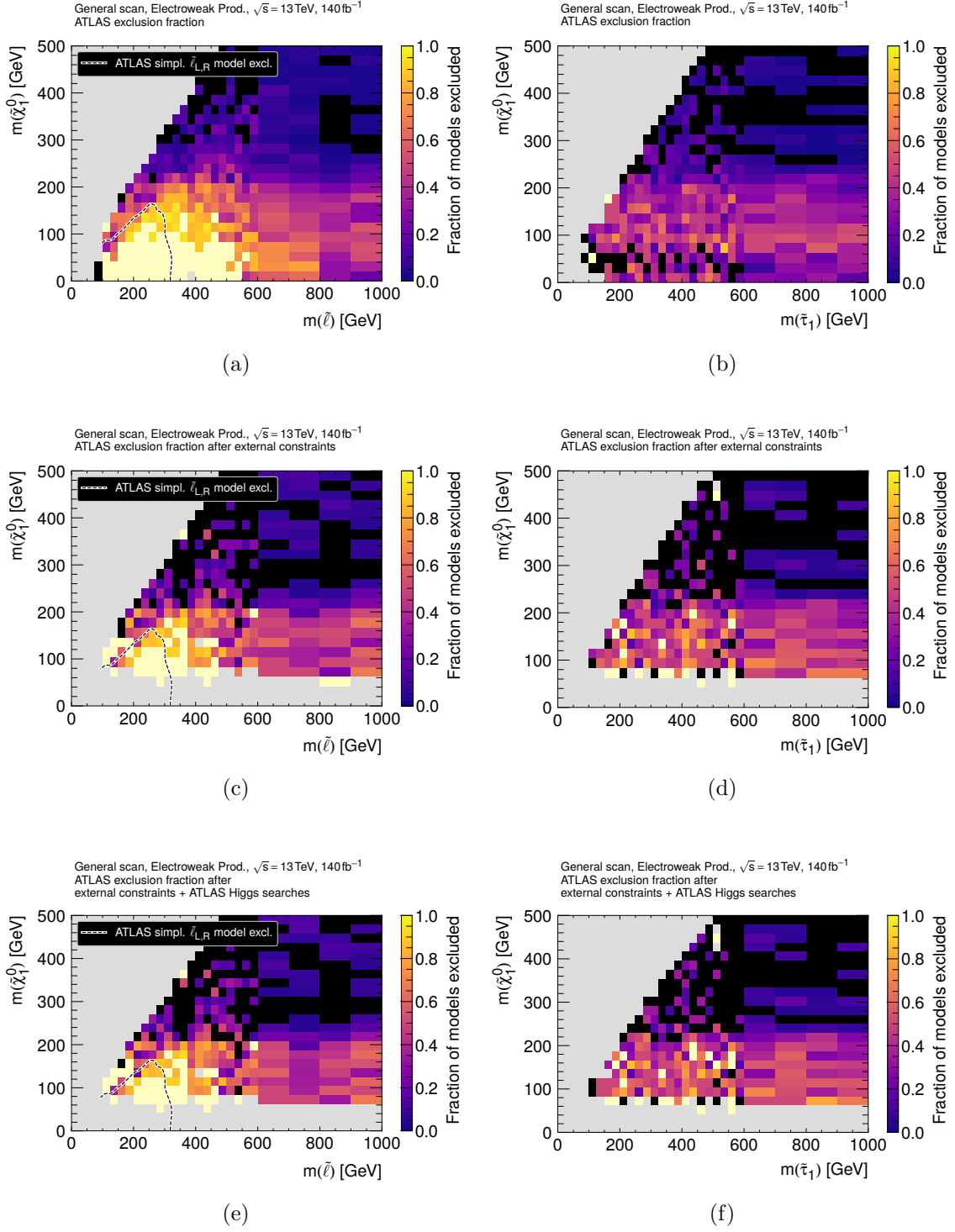


Figure 7.13: The fraction of General scan models excluded by ATLAS Run 2 SUSY results. The first column, (a) (c) (e), displays the  $m(\tilde{l})$  vs.  $m(\tilde{\chi}_1^0)$  plane, while the second column, (b) (d) (f), illustrates the  $m(\tilde{\tau})$  vs.  $m(\tilde{\chi}_1^0)$  plane. The top row includes all models, the second row shows models that satisfy all external constraints, and the third row presents models that pass both external constraints and ATLAS Higgs searches.

#### 7.4.4 Complementarity with Dark Matter Detection Experiments

Experiments that directly detect **DM** are also helpful in investigating **SUSY** scenarios involving a **DM** candidate. The constraints from two direct detection experiments discussed in this section are as follows:

1. **LUX-ZEPLIN (LZ)** [172]: Currently, **LZ** sets the most stringent limits on the spin-independent **WIMP**-nucleon scattering cross-section.
2. **PICO-60** [173]: At present, PICO-60 provides the tightest constraints on the spin-dependent **WIMP**-proton scattering cross-section.

This section explores the sensitivity of these experiments and their complementarity with **ATLAS**. It is essential to mention that the limits from both **LZ** and PICO-60 assume a **DM** candidate consistent with the observed **DM** relic density,  $\Omega h^2 = 0.12$ . However, most models in the **pMSSM** scans yield lower values than the relic density observed. Consequently, all of the **WIMP**-nucleon scattering cross-sections displayed in this section, including both those calculated for **pMSSM** models and the experimental upper limits are scaled by  $(\Omega h^2)/0.12$  (i.e., the ratio of the expected to observed relic density) to provide a fair comparison.

Figure 7.14 shows the **ATLAS SUSY** research constraints on the  $m(\tilde{\chi}_1^0) - \Omega h^2$  plane. Figure 7.14a presents the results considering only the constraints from direct **ATLAS** searches, without incorporating any external constraints. At the same time, there are relatively fewer models but high exclusion fractions as well in the  $Z/h$  funnel regions<sup>2</sup>. By comparing Figures from 7.14a to 7.14d, the excluded fraction of models become more strong as more constraints are applied, particularly when including all external constraints which basically includes the **DM** constraints. It can also be observed that direct detection experiments impose strong constraints on the  $Z/h$ -funnel region. After considering the constraints from the **ATLAS** experiment, models in the  $Z/h$ -funnel region are almost entirely excluded. In contrast, the **ATLAS** and other experiments impose lower constraints on high-mass **LSP** particles. **LSP** particles with masses close to 2 TeV can pass all experimental constraints, but the possibility of **LSP** particles as **DM** particles with masses in the range of 1 to 100 GeV is very low.

To investigate the effects of experimental constraints on **LSP** in more detail, Figure 7.15 displays the exclusion ratio of **SUSY** constraints for all models, which satisfy experimental

---

<sup>2</sup>The  $Z/h$ -funnel region is significant because it corresponds to enhanced annihilation rates of dark matter particles through the s-channel exchange of a  $Z$  or Higgs boson, leading to a relic density in agreement with observed dark matter density. In the  $m(\tilde{\chi}_1^0) - \Omega h^2$  plane, the  $Z/h$ -funnel region can be identified as follows:

- **$Z$ -funnel region:** Where  $m(\tilde{\chi}_1^0) \approx \frac{m_Z}{2} \approx 45$  GeV.
- **$h$ -funnel region:** Where  $m(\tilde{\chi}_1^0) \approx \frac{m_h}{2} \approx 62.5$  GeV.

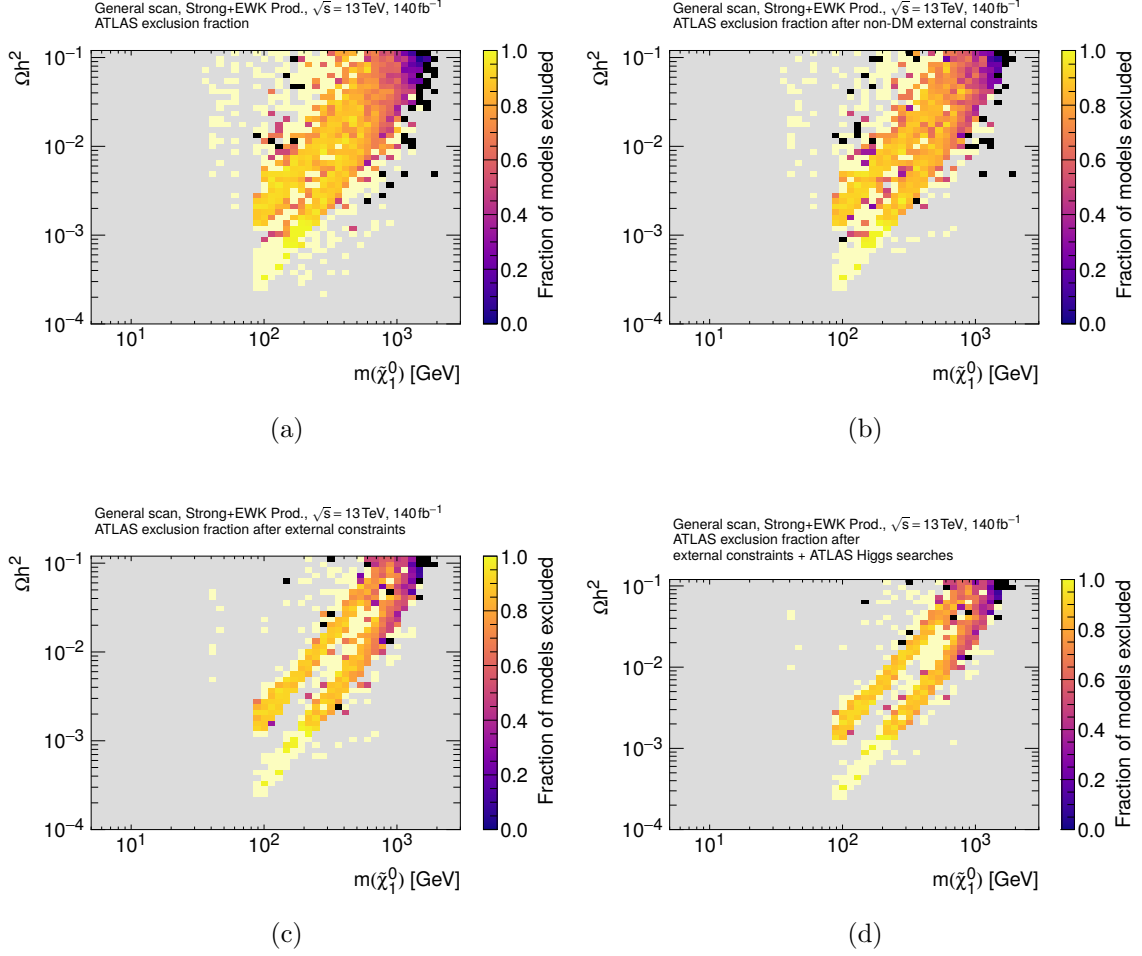


Figure 7.14: Exclusion of models from the General scan in the  $m(\tilde{\chi}_1^0)$  vs.  $\Omega h^2$  with (a) all models, (b) models with all non-dark matter constraints, (c) models with all external constraints applied, and (d) models with all external constraints and ATLAS Higgs searches applied.

constraints from non-**ATLAS** sources, except for direct experiments on dark matter detection, and models that have had constraints imposed from **ATLAS** Higgs studies and all other sources of constraints. It can be found that the **ATLAS** experimental constraints can exclude regions that direct **DM** detection experiments cannot exclude. Conversely, for  $\sigma_{\text{SI}}$ , the direct detection experiments can exclude high-mass **LSP** particles that the **ATLAS** experimental constraints cannot exclude.

#### 7.4.5 Complementary and Overlap of ATLAS Experiment Constraints with Other Experiment

Figure 7.16 summarizes the degree of overlap for each experimental constraint. The numbers on the diagonal represent the ratio of models excluded by the corresponding constraints, while the numbers off the diagonal represent the ratio of models excluded by both constraints. By



observing Figure 7.16a, it can be found that the analysis constraints of strong coupling production SUSY particles are highly overlapping. The overlap between 2L, 3L, and 4L analysis is significant due to the complexity of SUSY particle decay channels in the **pMSSM** model. At the same time, Disappearing-track analysis overlap is significantly minimal compared to other

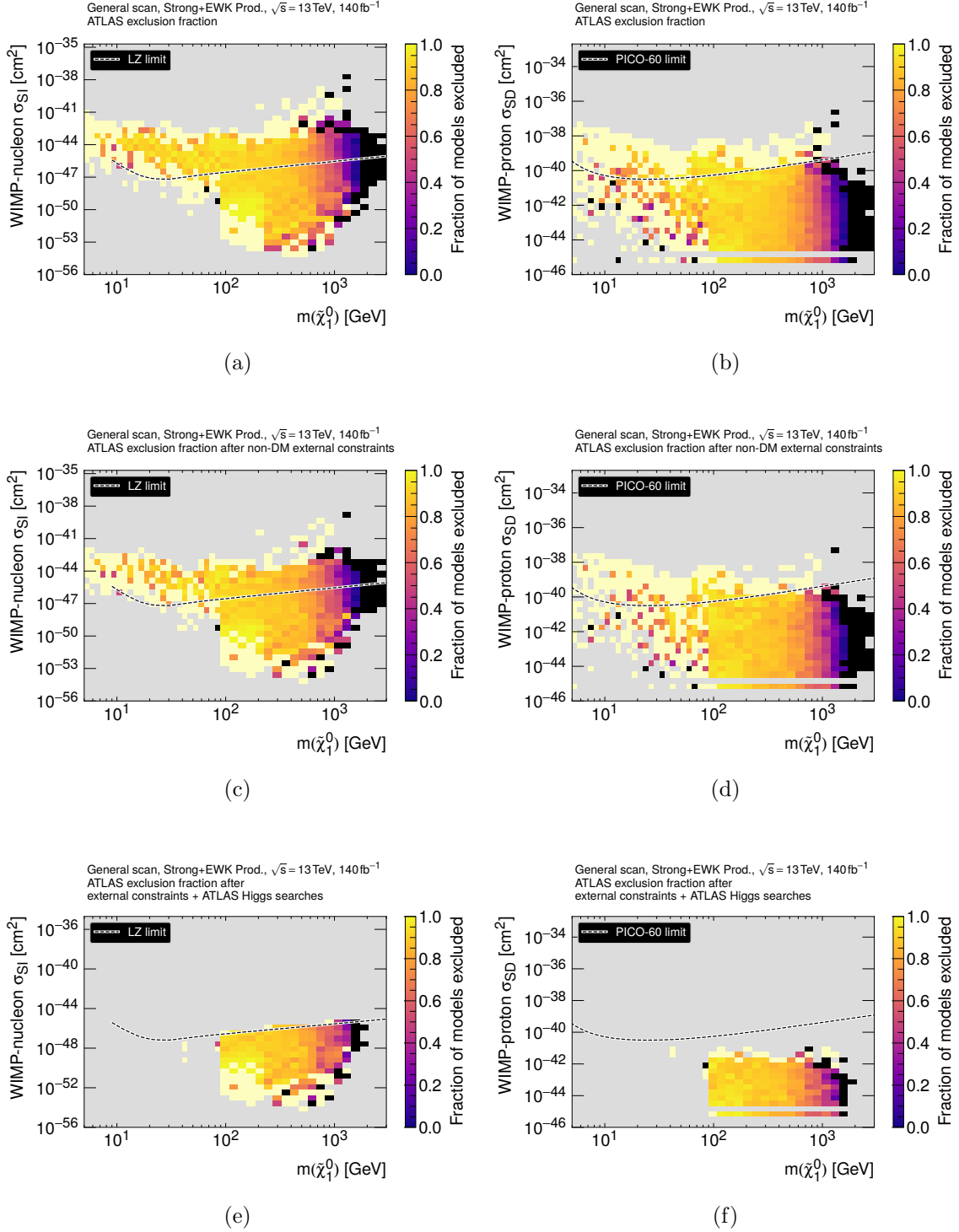
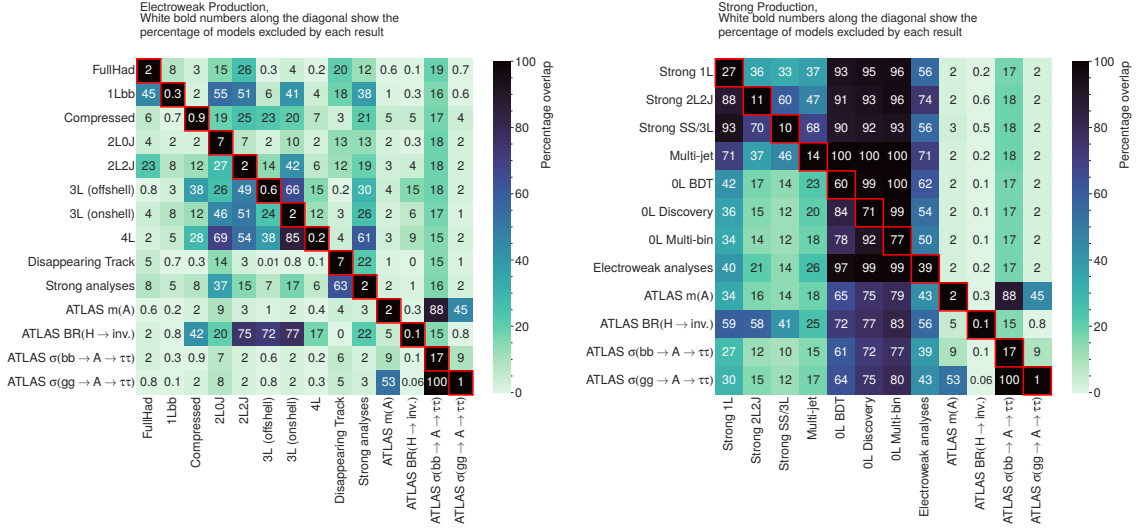


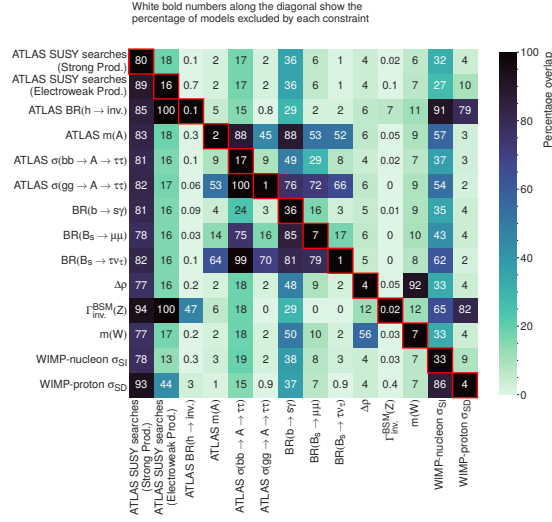
Figure 7.15: Fraction of models excluded by the ATLAS Run 2 searches in the (a)(c)(e)  $m(\tilde{\chi}_1^0)$  vs. WIMP-nucleon spin-independent scattering cross-section plane and (b)(d)(f)  $m(\tilde{\chi}_1^0)$  vs. WIMP-nucleon spin-dependent scattering cross-section plane.

analyses. In Figure 7.16b, we can see that the Strong 0L analysis overlaps significantly with most other analyses. In addition, Strong 1L, 2L2J, SS/3L, and Multi-jet analyses have a lot of overlap ratio due to the similarities in their analysis methods. Figure 7.16c shows the overlap between ATLAS SUSY, Higgs, and non-ATLAS exclusions. Notably,  $B(h \rightarrow \text{inv})$  exclusion, SUSY experiment exclusions, **Z width**, and **DM** direct detection experiment exclusions have a high overlap ratio.

Figure 7.17 summarises the constraints from the ATLAS experiment on the masses of SUSY particles. Figures 7.17a and 7.17b show the exclusion capabilities of the ATLAS experiment on **EWkino** and the third-generation  $\tilde{l}$ , where **EWkino** in Figure 7.17a only considers production through **EW** processes, while Figure 7.17b considers cases where  $\tilde{g}$  or  $\tilde{q}$  decay is involved. It can be seen that considering strong interaction production processes can significantly expand the exclusion range of the **pMSSM** model, though it does not completely exclude the **pMSSM** range. Lighter **EWkino** is still not entirely excluded. Figure 7.17c shows that in the region  $m(\tilde{g}) \leq 1500$  TeV and  $m(\tilde{q}) \leq 550$  GeV, the **pMSSM** model is almost completely excluded.



(a) Electroweak Production: Overlaps between searches. (b) Strong Production: Overlaps between searches.



(c) Overlaps between external constraints.

Figure 7.16: Percentage overlap in models excluded by each search and constraint. The diagonal entries show the percentage of all models excluded by that specific search/constraint, with the number in bold. In the off-diagonal squares, the numbers and colors represent the percentage of models excluded by the result on the y-axis that are also excluded by the result on the x-axis, calculated as  $100 \times N_{xy}/N_y$ , where  $N_{xy}$  is the count of models excluded by both the x- and y-axis results, and  $N_y$  is the count of models excluded by the y-axis result.

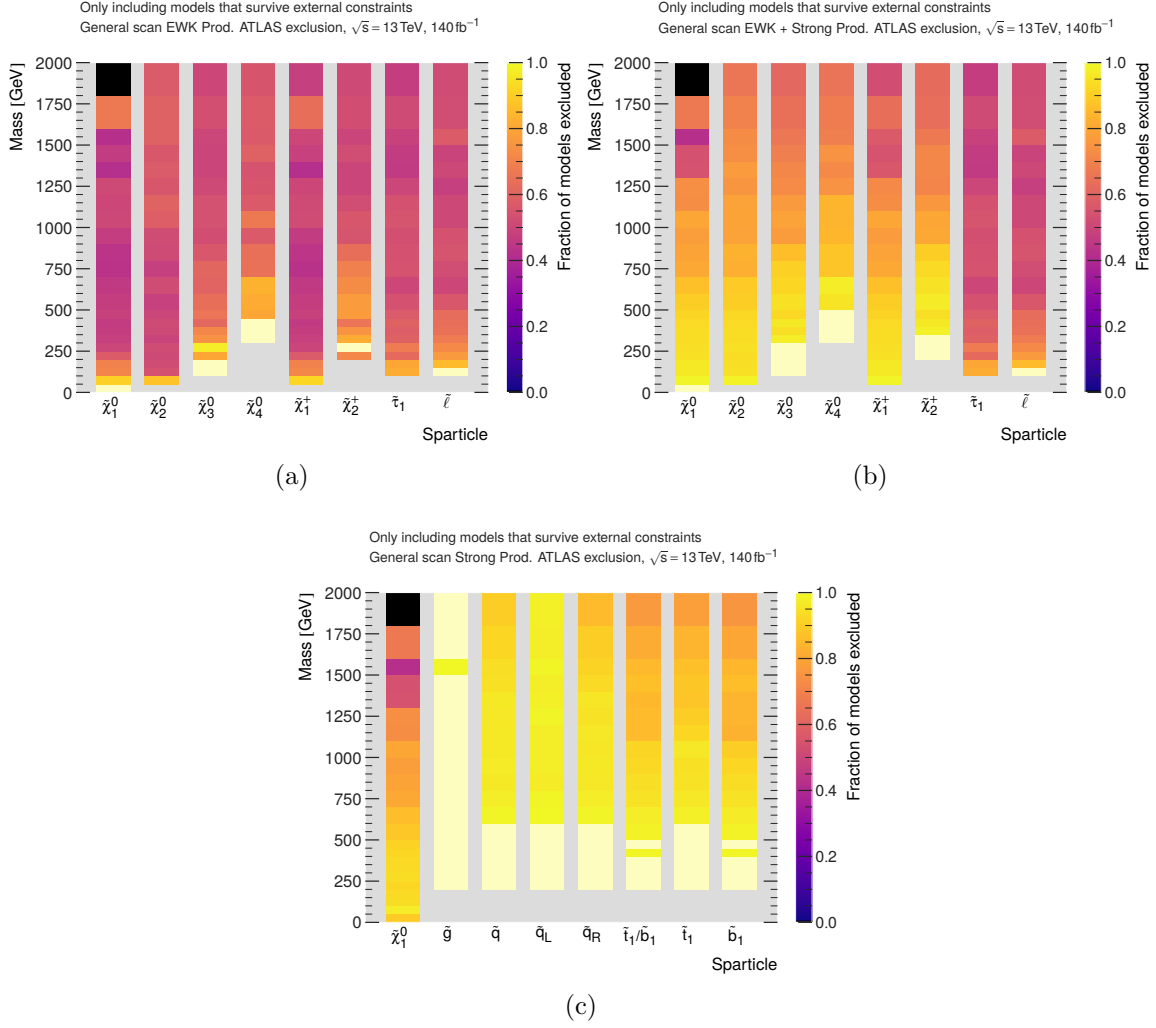


Figure 7.17: Summary plots showing the fraction of models excluded by ATLAS across the masses of each sparticle for models which pass external constraints. (a) shows the EWkinos and sleptons of electroweak production, (b) considers electroweak and Strong production for EWkinos, and (c) shows the summary of  $\tilde{\chi}_1^0$ ,  $\tilde{g}$  and third-generation  $\tilde{q}$ .

## 7.5 Summary

My own contributions to this analysis began with familiarising the workflow of the analysis software framework [198, 199] by generating a small number of models. Once I fully grasped the framework, I conducted a detailed constraints study, identifying the most recent results and relevant constraint ranges.

Subsequently, I executed my scan through several stages, which involved submitting multiple grid jobs and performing regular checks to ensure smooth execution and correct any encountered errors. After refining the models to their final form, I generated exclusion plots by adapting the plotting framework previously used for the **EW pMSSM** Run2 paper.

Additionally, I dedicated time to compile and integrate the results into the official **ATLAS**

internal note. This note summarised the outcomes of four scans: my own general **pMSSM** scan, a dark matter **DM** scan, a third-generation scan focused on 3rd generation sleptons and squarks, and a third-generation **DM** scan.

This analysis aimed to show the studies performed by **ATLAS** during Run2 in the 19D **pMSSM** model, with the consideration of **LSP** being  $\tilde{\chi}_1^0$  in the **pMSSM** model. This analysis investigates the impact of **ATLAS** experimental constraints on **SUSY** particle masses in the **pMSSM** model and the relationship between collider and non-collider experimental constraints on **pMSSM** models. The study shows that:

1. The exclusion limits of **SUSY** particle mass parameters in the **pMSSM** model by **ATLAS** experiments are smaller than those based on simplified models. In contrast, the constraints on  $\tilde{q}$  masses in the **pMSSM** model are slightly stronger than those based on simplified models.
2. There is still a good chance that **SUSY** models in the compressed mass region have not been excluded yet. Future **SUSY** analyses should focus on this area, especially the **EWkino** particles in the mass compression region.

Overall, this analysis summarises the experimental results from the **ATLAS** experiment during Run2 and provides essential references for future **SUSY** searches.

# Chapter 8

## Summary and Conclusions

The Standard Model (**SM**) is one of the most successful theories in science. Regardless, it has some limitations and cannot explain everything about the fundamental nature of the universe. Supersymmetry (**SUSY**) is one of the main theories proposed to go beyond the Standard Model **BSM**. The basics of both the **SM** and **SUSY** are discussed in the introduction chapter of this thesis.

To validate any theory, it must be tested through experiments. The Large Hadron Collider (**LHC**) is one of the largest and most powerful accelerators built for such purposes. Chapter 3 of this thesis provides an introduction to the **LHC** and focuses on one of its main detectors, **ATLAS**. This chapter also explains the process of reconstructing and identifying fundamental particles within the detector.

Two **ATLAS** performance studies are conducted in this thesis, containing my contributions in collaboration with combined performance groups. The results of these studies are derived from **ATLAS** Run 2 data at a luminosity of  $139 \text{ fb}^{-1}$ , with some checks also performed using early Run 3 data. These two performance studies are summarized as follows:

1. **Electron Reconstruction Efficiencies:** This study focuses on the reconstruction efficiency of electrons. All the details for this project are in chapter 4. I dedicated approximately one year of my PhD to this project, known as the **ATLAS** Qualification Task, through which I attained **ATLAS** author status. My primary contributions to this project involved helping to develop the method within a new, more Python-based framework instead of the traditional C++ framework. Additionally, I validated the measurements against the old framework. All comparisons were thoroughly validated. The methodology and results of these measurements are documented in an **ATLAS** internal note, as referenced in [\[107\]](#).

2. **Fake track studies in the dense environment of ATLAS detector:** The second study investigates the rate of fake tracks in the dense environment of the **ATLAS** detector. This research was a collaborative effort by the **ATLAS** Clustering and Tracking in Dense Environment (CTIDE) group, with comprehensive details provided in Chapter 5. The study employed a Control Region method to determine the fake track rate, which was further validated using two additional methods. All the details for this project are in chapter 5. The methodology and results of these measurements are documented in an **ATLAS** internal note, as referenced in [119].

These studies contribute to the ongoing efforts to refine the **ATLAS** detector’s performance, ensuring it remains a vital tool for exploring the fundamental questions of particle physics and testing theories **BSSM!** (**BSSM!**).

Among all theories **BSM**, **SUSY** offers numerous advantages. **SUSY** can be naturally incorporated into the framework of quantum field theory. This extension preserves the mathematical consistency of quantum field theory while addressing issues like the hierarchy problem. **SUSY** also ensures that the coupling constants of the three gauge interactions can converge at the grand unification energy scale. However, this unification does not occur in all cases and depends on specific assumptions. Nevertheless, a significant drawback of the **SUSY** model is the lack of evidence for supersymmetric particles in current searches, as well as the absence of other particles predicted by new physics. To address this issue, this thesis conducts two related studies:

1. **Expanding the gluino exclusion limits:** This research has broadened the search for supersymmetric gluinos in events with an intense jet and missing transverse momentum. Details are provided in chapter 6. Our findings show that the excluded region in the gluino mass spectrum has been extended, reaching up to 1000 GeV for low gluino-neutralino mass differences. The **ATLAS SUSY** searches did not explicitly exclude these regions.
2. **Investigating the exclusion scenarios of more complex SUSY models, focusing on the 19D pMSSM model:** The main analysis performed during my PhD, which aims to constrain the 19D **pMSSM** model to help evaluate the limitations and exclusions of the **ATLAS** experiment for more realistic **SUSY** models, providing valuable insights for future **SUSY** searches. The analysis demonstrates the **ATLAS SUSY** searches during Run 2 within the **pMSSM** model framework. The **SUSY** models in the mass compression region still have a large potential for not being excluded. Details are provided in chapter 7. Additionally, the exclusion range of  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  in the **pMSSM** model is much smaller than the exclusion limits of simplified models.

# Conferences and publications related to the subject of this thesis

## Published Article

- Hammad Rasheed, Ioana Duminica, “Expanding the gluino exclusion limits using events with one highly energetic final state jet and missing transverse momentum”, Romanian Journal of Physics 69 (7-8), 404 (2024) <https://rjp.nipne.ro/RomJPhys.2024.69.404>

## ATLAS Internal Notes

- Hammad Rasheed, Otilia Anamaria Ducu, and Julien Maurer, “Rate of fake tracks in dense environments (Rel22/23)”, ATL-COM-PHYS-2023-423, 2023. <https://cds.cern.ch/record/2859907>
- Hammad Rasheed, “Electron reconstruction efficiency and scale factors measurements for reprocessed Run-2 and early Run-3 data”, ATL-COM-PHYS-2022-1025, 2022. <https://cds.cern.ch/record/2839210>

## International Conferences

- Hammad Rasheed, “ATLAS searches for electroweak supersymmetry with compressed spectra” **Oral Presentation** at XIII International Conference on New Frontiers in Physics, Kolymbari, Crete, Greece, 26 August – 4 September 2024, <https://indi.to/VQK4V>
- Hammad Rasheed, “Phenomenological Minimal Supersymmetry Scan using Run 2 ATLAS searches ( $139\text{ fb}^{-1}$  AT  $\sqrt{S} = 13\text{ TeV}$ )”, **Oral Presentation** at 21st International Balkan Workshop on Applied Physics and Materials Science, Constanta, Romania, 11-14, July, 2023, Published Abstracts: <https://ibwap.ro/wp-content/uploads/2024/03/book-abstracts-ibwap-2023.pdf>.



# List of Co-Authored ATLAS Publications

- ATLAS Collaboration, “Accuracy versus precision in boosted top tagging with the ATLAS detector,” *JINST*, vol. 19, no. 8, p. P08018, Year: 2024. <https://doi.org/10.1088/1748-0221/19/08/P08018>.
- ATLAS Collaboration, “Measurement of single top-quark production in association with a W boson in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 7, p. 072010, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.072010>.
- ATLAS Collaboration, “Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using pp collisions at  $\sqrt{s} = 13$  TeV,” *JHEP*, vol. 11, p. 036, Year: 2024. [https://doi.org/10.1007/JHEP11\(2024\)036](https://doi.org/10.1007/JHEP11(2024)036).
- ATLAS Collaboration, “Sensor response and radiation damage effects for 3D pixels in the ATLAS IBL Detector,” *JINST*, vol. 19, no. 10, p. P10008, Year: 2024. <https://doi.org/10.1088/1748-0221/19/10/P10008>.
- ATLAS Collaboration, “Search for decays of the Higgs boson into a pair of pseudoscalar particles decaying into  $b\bar{b}\tau^+\tau^-$  using pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 5, p. 052013, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.052013>.
- ATLAS Collaboration, “Measurement of differential cross-sections in  $t\bar{t}$  and  $t\bar{t} + \text{jets}$  production in the lepton+jets final state in pp collisions at  $\sqrt{s} = 13$  TeV using 140 fb $^{-1}$  of ATLAS data,” *JHEP*, vol. 08, p. 182, Year: 2024. [https://doi.org/10.1007/JHEP08\(2024\)182](https://doi.org/10.1007/JHEP08(2024)182).
- ATLAS Collaboration, “Search for R-parity violating supersymmetric decays of the top squark to a b-jet and a lepton in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 9, p. 092004, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.092004>.

[PhysRevD.110.092004](#).

- ATLAS Collaboration, “Combination of Searches for Higgs Boson Pair Production in pp Collisions at  $\sqrt{s} = 13$  TeV with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 133, no. 10, p. 101801, Year: 2024. <https://doi.org/10.1103/PhysRevLett.133.101801>.
- ATLAS Collaboration, “Combination of searches for Higgs boson decays into a photon and a massless dark photon using pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 08, p. 153, Year: 2024. [https://doi.org/10.1007/JHEP08\(2024\)153](https://doi.org/10.1007/JHEP08(2024)153).
- ATLAS Collaboration, “Search for a resonance decaying into a scalar particle and a Higgs boson in final states with leptons and two photons in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 10, p. 104, Year: 2024. [https://doi.org/10.1007/JHEP10\(2024\)104](https://doi.org/10.1007/JHEP10(2024)104).
- ATLAS Collaboration, “Measurements of jet cross-section ratios in 13 TeV proton-proton collisions with ATLAS,” *Phys. Rev. D*, vol. 110, no. 7, p. 072019, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.072019>.
- ATLAS Collaboration, “Search for pair-produced vectorlike quarks coupling to light quarks in the lepton plus jets final state using 13 TeV pp collisions with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 5, p. 052009, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.052009>.
- ATLAS Collaboration, “Search for dark mesons decaying to top and bottom quarks in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 09, p. 005, Year: 2024. [https://doi.org/10.1007/JHEP09\(2024\)005](https://doi.org/10.1007/JHEP09(2024)005).
- ATLAS Collaboration, “Search for non-resonant Higgs boson pair production in final states with leptons, taus, and photons in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 08, p. 164, Year: 2024. [https://doi.org/10.1007/JHEP08\(2024\)164](https://doi.org/10.1007/JHEP08(2024)164).
- ATLAS Collaboration, “Calibration of a soft secondary vertex tagger using proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 3, p. 032015, Year: 2024. <https://doi.org/10.1103/PhysRevD.110.032015>.
- ATLAS Collaboration, “Beam-induced backgrounds measured in the ATLAS detector during local gas injection into the LHC beam vacuum,” *JINST*, vol. 19, no. 6, p. P06014, Year: 2024. <https://doi.org/10.1088/1748-0221/19/06/P06014>.
- ATLAS Collaboration, “Search for heavy neutral Higgs bosons decaying into a top quark pair in  $140\text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 08, p. 013, Year: 2024. [https://doi.org/10.1007/JHEP08\(2024\)013](https://doi.org/10.1007/JHEP08(2024)013).

- ATLAS Collaboration, “Search for pair production of boosted Higgs bosons via vector-boson fusion in the  $b\bar{b}b\bar{b}$  final state using pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 858, p. 139007, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.139007>.
- ATLAS Collaboration, “Search for exclusive Higgs boson decays into  $D^*\gamma$  and Z boson decays into  $D^0\gamma$  and  $K_s^0\gamma$  in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 855, p. 138762, 2024. <https://doi.org/10.1016/j.physletb.2024.138762>.
- ATLAS Collaboration, “Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 133, no. 10, p. 101802, 2024. <https://doi.org/10.1103/PhysRevLett.133.101802>.
- ATLAS Collaboration, “Search for new particles in final states with a boosted top quark and missing transverse momentum in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 05, p. 263, 2024. [https://doi.org/10.1007/JHEP05\(2024\)263](https://doi.org/10.1007/JHEP05(2024)263).
- ATLAS Collaboration, “Search for a new  $Z'$  gauge boson via the  $pp \rightarrow W^\pm \rightarrow Z'\mu^\pm \nu \rightarrow \mu^\pm \mu^\mp \mu^\pm \nu$  process in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 7, p. 072008, 2024. <https://doi.org/10.1103/PhysRevD.110.072008>.
- ATLAS Collaboration, “A search for top-squark pair production, in final states containing a top quark, a charm quark and missing transverse momentum, using the 139 fb $^{-1}$  of pp collision data collected by the ATLAS detector,” *JHEP*, vol. 07, p. 250, 2024. [https://doi.org/10.1007/JHEP07\(2024\)250](https://doi.org/10.1007/JHEP07(2024)250).
- ATLAS Collaboration, “Combination of searches for heavy spin-1 resonances using 139 fb $^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 04, p. 118, 2024. [https://doi.org/10.1007/JHEP04\(2024\)118](https://doi.org/10.1007/JHEP04(2024)118).
- ATLAS Collaboration, “Statistical Combination of ATLAS Run 2 Searches for Charginos and Neutralinos at the LHC,” *Phys. Rev. Lett.*, vol. 133, no. 3, p. 031802, 2024. <https://doi.org/10.1103/PhysRevLett.133.031802>.
- ATLAS, CMS Collaboration, “Combination of Measurements of the Top Quark Mass from Data Collected by the ATLAS and CMS Experiments at  $s = 7$  and 8 TeV,” *Phys. Rev. Lett.*, vol. 132, no. 26, p. 261902, 2024. <https://doi.org/10.1103/PhysRevLett.132.261902>.
- ATLAS Collaboration, “Performance of the ATLAS forward proton Time-of-Flight de-

- tector in Run 2,” *JINST*, vol. 19, no. 05, p. P05054, 2024. <https://doi.org/10.1088/1748-0221/19/05/P05054>.
- ATLAS Collaboration, “ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM,” *JHEP*, vol. 05, p. 106, 2024. [https://doi.org/10.1007/JHEP05\(2024\)106](https://doi.org/10.1007/JHEP05(2024)106).
  - ATLAS Collaboration, “Determination of the Relative Sign of the Higgs Boson Couplings to W and Z Bosons Using WH Production via Vector-Boson Fusion with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 133, no. 14, p. 141801, 2024. <https://doi.org/10.1103/PhysRevLett.133.141801>.
  - ATLAS Collaboration, “Search for electroweak production of supersymmetric particles in final states with two  $\tau$ -leptons in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector,” *JHEP*, vol. 05, p. 150, 2024. [https://doi.org/10.1007/JHEP05\(2024\)150](https://doi.org/10.1007/JHEP05(2024)150).
  - ATLAS Collaboration, “Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment,” *Phys. Lett. B*, vol. 854, p. 138743, 2024. <https://doi.org/10.1016/j.physletb.2024.138743>.
  - ATLAS Collaboration, “A search for R-parity-violating supersymmetry in final states containing many jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 05, p. 003, 2024. [https://doi.org/10.1007/JHEP05\(2024\)003](https://doi.org/10.1007/JHEP05(2024)003).
  - ATLAS Collaboration, “Search for pair production of higgsinos in events with two Higgs bosons and missing transverse momentum in  $s = 13$  TeV pp collisions at the ATLAS experiment,” *Phys. Rev. D*, vol. 109, no. 11, p. 112011, 2024. <https://doi.org/10.1103/PhysRevD.109.112011>.
  - ATLAS Collaboration, “Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks in pp Collisions at  $s = 13$  TeV with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 22, p. 221801, 2024. <https://doi.org/10.1103/PhysRevLett.132.221801>.
  - ATLAS Collaboration, “Search for new phenomena with top-quark pairs and large missing transverse momentum using  $140 \text{ fb}^{-1}$  of pp collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 03, p. 139, 2024. [https://doi.org/10.1007/JHEP03\(2024\)139](https://doi.org/10.1007/JHEP03(2024)139).
  - ATLAS Collaboration, “Combination of searches for pair-produced leptoquarks at  $s = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 854, p. 138736, 2024. <https://doi.org/10.1016/j.physletb.2024.138736>.
  - ATLAS Collaboration, “The ATLAS trigger system for LHC Run 3 and trigger perfor-

- mance in 2022,” *JINST*, vol. 19, no. 06, p. P06029, 2024. <https://doi.org/10.1088/1748-0221/19/06/P06029>.
- ATLAS Collaboration, “Measurement of the total and differential cross-sections of  $t\bar{t}W$  production in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 05, p. 131, Year: 2024. [https://doi.org/10.1007/JHEP05\(2024\)131](https://doi.org/10.1007/JHEP05(2024)131).
  - ATLAS Collaboration, “Search for heavy resonances in final states with four leptons and missing transverse momentum or jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 10, p. 130, Year: 2024. [https://doi.org/10.1007/JHEP10\(2024\)130](https://doi.org/10.1007/JHEP10(2024)130).
  - ATLAS Collaboration, “Study of High-Transverse-Momentum Higgs Boson Production in Association with a Vector Boson in the qqbb Final State with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 13, p. 131802, Year: 2024. <https://doi.org/10.1103/PhysRevLett.132.131802>.
  - ATLAS Collaboration, “Inclusive and differential cross-section measurements of  $t\bar{t}Z$  production in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector, including EFT and spin-correlation interpretations,” *JHEP*, vol. 07, p. 163, Year: 2024. [https://doi.org/10.1007/JHEP07\(2024\)163](https://doi.org/10.1007/JHEP07(2024)163).
  - ATLAS Collaboration, “Search for short- and long-lived axion-like particles in  $H \rightarrow aa \rightarrow 4\gamma$  decays with the ATLAS experiment at the LHC,” *Eur. Phys. J. C*, vol. 84, no. 7, p. 742, Year: 2024. <https://doi.org/10.1140/epjc/s10052-024-12979-0>.
  - ATLAS Collaboration, “Measurement of jet substructure in boosted  $t\bar{t}$  events with the ATLAS detector using 140 fb $^{-1}$  of 13 TeV proton-proton collisions,” *Phys. Rev. D*, vol. 109, no. 11, p. 112016, Year: 2024. <https://doi.org/10.1103/PhysRevD.109.112016>.
  - ATLAS Collaboration, “Measurement of the Z boson invisible width at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 854, p. 138705, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.138705>.
  - ATLAS Collaboration, “Search for the decay of the Higgs boson to a Z boson and a light pseudoscalar particle decaying to two photons,” *Phys. Lett. B*, vol. 850, p. 138536, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.138536>.
  - ATLAS Collaboration, “Measurement of the  $VH, H \rightarrow \tau\tau$  process with the ATLAS detector at 13 TeV,” *Phys. Lett. B*, vol. 855, p. 138817, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.138817>.
  - ATLAS Collaboration, “Measurement and interpretation of same-sign W boson pair production in association with two jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV with

- the ATLAS detector,” *JHEP*, vol. 04, p. 026, Year: 2024. [https://doi.org/10.1007/JHEP04\(2024\)026](https://doi.org/10.1007/JHEP04(2024)026).
- ATLAS Collaboration, “Search for light long-lived neutral particles from Higgs boson decays via vector-boson-fusion production in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Eur. Phys. J. C*, vol. 84, no. 7, p. 719, Year: 2024. <https://doi.org/10.1140/epjc/s10052-024-12902-7>.
  - ATLAS Collaboration, “Combination of Searches for Resonant Higgs Boson Pair Production Using Proton-Proton Collisions at  $\sqrt{s} = 13$  TeV with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 23, p. 231801, Year: 2024. <https://doi.org/10.1103/PhysRevLett.132.231801>.
  - ATLAS Collaboration, “Measurement of ZZ production cross-sections in the four-lepton final state in proton-proton collisions at  $\sqrt{s} = 13.6$  TeV with the ATLAS experiment,” *Phys. Lett. B*, vol. 855, p. 138764, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.138764>.
  - ATLAS Collaboration, “Simultaneous energy and mass calibration of large-radius jets with the ATLAS detector using a deep neural network,” *Mach. Learn. Sci. Tech.*, vol. 5, no. 3, p. 035051, Year: 2024. <https://doi.org/10.1088/2632-2153/ad611e>.
  - ATLAS Collaboration, “Observation of quantum entanglement with top quarks at the ATLAS detector,” *Nature*, vol. 633, no. 8030, pp. 542–547, Year: 2024. <https://doi.org/10.1038/s41586-024-07824-z>.
  - ATLAS Collaboration, “Search for a CP-odd Higgs boson decaying into a heavy CP-even Higgs boson and a Z boson in the  $\ell^+\ell^-t\bar{t}$  and  $\nu\bar{\nu}b\bar{b}$  final states using 140 fb $^{-1}$  of data collected with the ATLAS detector,” *JHEP*, vol. 02, p. 197, Year: 2024. [https://doi.org/10.1007/JHEP02\(2024\)197](https://doi.org/10.1007/JHEP02(2024)197).
  - ATLAS Collaboration, “Search for resonant production of dark quarks in the dijet final state with the ATLAS detector,” *JHEP*, vol. 02, p. 128, Year: 2024. [https://doi.org/10.1007/JHEP02\(2024\)128](https://doi.org/10.1007/JHEP02(2024)128).
  - ATLAS Collaboration, “Improving topological cluster reconstruction using calorimeter cell timing in ATLAS,” *Eur. Phys. J. C*, vol. 84, no. 5, p. 455, Year: 2024. <https://doi.org/10.1140/epjc/s10052-024-12657-1>.
  - ATLAS Collaboration, “Studies of new Higgs boson interactions through nonresonant HH production in the  $b\bar{b}\gamma\gamma$  final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 01, p. 066, Year: 2024. [https://doi.org/10.1007/JHEP01\(2024\)066](https://doi.org/10.1007/JHEP01(2024)066).
  - ATLAS Collaboration, “Search for non-resonant Higgs boson pair production in the  $2b +$

- $2\ell + E_{\text{T}}^{\text{miss}}$  final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 02, p. 037, Year: 2024. [https://doi.org/10.1007/JHEP02\(2024\)037](https://doi.org/10.1007/JHEP02(2024)037).
- ATLAS Collaboration, “Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 12, p. 167, Year: 2023. [https://doi.org/10.1007/JHEP12\(2023\)167](https://doi.org/10.1007/JHEP12(2023)167).
  - ATLAS Collaboration, “Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in  $ZZ \rightarrow 4\ell$  events with the ATLAS detector at  $\sqrt{s} = 13$  TeV,” *JHEP*, vol. 12, p. 107, Year: 2023. [https://doi.org/10.1007/JHEP12\(2023\)107](https://doi.org/10.1007/JHEP12(2023)107).
  - ATLAS Collaboration, “Measurement of t-channel single-top-quark production in pp collisions at  $s = 5.02$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 854, p. 138726, Year: 2024. <https://doi.org/10.1016/j.physletb.2024.138726>.
  - ATLAS Collaboration, “Measurement of the production cross-section of  $J/\psi$  and  $\psi(2S)$  mesons in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Eur. Phys. J. C*, vol. 84, no. 2, p. 169, Year: 2024. <https://doi.org/10.1140/epjc/s10052-024-12439-9>.
  - ATLAS Collaboration, “Search for the Exclusive W Boson Hadronic Decays  $W^{\pm} \rightarrow \pi^{\pm}\gamma$ ,  $W^{\pm} \rightarrow K^{\pm}\gamma$  and  $W^{\pm} \rightarrow \rho^{\pm}\gamma$  with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 133, no. 16, p. 161804, Year: 2024. <https://doi.org/10.1103/PhysRevLett.133.161804>.
  - ATLAS Collaboration, “Search for flavour-changing neutral tqH interactions with  $H \rightarrow \gamma\gamma$  in pp collisions at  $\sqrt{s} = 13$  TeV using the ATLAS detector,” *JHEP*, vol. 12, p. 195, Year: 2023. [https://doi.org/10.1007/JHEP12\(2023\)195](https://doi.org/10.1007/JHEP12(2023)195).
  - ATLAS Collaboration, “Electron and photon energy calibration with the ATLAS detector using LHC Run 2 data,” *JINST*, vol. 19, no. 02, p. P02009, Year: 2024. <https://doi.org/10.1088/1748-0221/19/02/P02009>.
  - ATLAS Collaboration, “Search for the  $Z\gamma$  decay mode of new high-mass resonances in pp collisions at  $s = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 848, p. 138394, Year: 2024. <https://doi.org/10.1016/j.physletb.2023.138394>.
  - ATLAS, CMS Collaboration, “Evidence for the Higgs Boson Decay to a Z Boson and a Photon at the LHC,” *Phys. Rev. Lett.*, vol. 132, no. 2, p. 021803, Year: 2024. <https://doi.org/10.1103/PhysRevLett.132.021803>.
  - ATLAS Collaboration, “Azimuthal Angle Correlations of Muons Produced via Heavy-Flavor Decays in 5.02 TeV Pb+Pb and pp Collisions with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 20, p. 202301, Year: 2024. <https://doi.org/10.1103/>



[PhysRevLett.132.202301](#).

- ATLAS Collaboration, “Measurement of the Centrality Dependence of the Dijet Yield in p+Pb Collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 10, p. 102301, Year: 2024. <https://doi.org/10.1103/PhysRevLett.132.102301>.
- ATLAS Collaboration, “Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment,” *JHEP*, vol. 05, p. 162, Year: 2024. [https://doi.org/10.1007/JHEP05\(2024\)162](https://doi.org/10.1007/JHEP05(2024)162).
- ATLAS Collaboration, “Differential cross-section measurements of the production of four charged leptons in association with two jets using the ATLAS detector,” *JHEP*, vol. 01, p. 004, Year: 2024. [https://doi.org/10.1007/JHEP01\(2024\)004](https://doi.org/10.1007/JHEP01(2024)004).
- ATLAS Collaboration, “Measurement of the  $t\bar{t}$  cross section and its ratio to the Z production cross section using pp collisions at  $\sqrt{s} = 13.6$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 848, p. 138376, Year: 2024. <https://doi.org/10.1016/j.physletb.2023.138376>.
- ATLAS Collaboration, “Software Performance of the ATLAS Track Reconstruction for LHC Run 3,” *Comput. Softw. Big Sci.*, vol. 8, no. 1, p. 9, Year: 2024. <https://doi.org/10.1007/s41781-023-00111-y>.
- ATLAS Collaboration, “Search for vector-boson resonances decaying into a top quark and a bottom quark using pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 12, p. 073, Year: 2023. [https://doi.org/10.1007/JHEP12\(2023\)073](https://doi.org/10.1007/JHEP12(2023)073).
- ATLAS Collaboration, “Measurement of the Higgs boson mass with  $H \rightarrow \gamma\gamma$  decays in  $140 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector,” *Phys. Lett. B*, vol. 847, p. 138315, Year: 2023. <https://doi.org/10.1016/j.physletb.2023.138315>.
- ATLAS Collaboration, “Search for magnetic monopoles and stable particles with high electric charges in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector,” *JHEP*, vol. 11, p. 112, Year: 2023. [https://doi.org/10.1007/JHEP11\(2023\)112](https://doi.org/10.1007/JHEP11(2023)112).
- ATLAS Collaboration, “Combined Measurement of the Higgs Boson Mass from the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  Decay Channels with the ATLAS Detector Using  $\sqrt{s} = 7, 8$ , and 13 TeV pp Collision Data,” *Phys. Rev. Lett.*, vol. 131, no. 25, p. 251802, Year: 2023. <https://doi.org/10.1103/PhysRevLett.131.251802>.
- ATLAS Collaboration, “Searches for exclusive Higgs boson decays into  $D^*\gamma$  and Z boson decays into  $D_0\gamma$  and  $K_s^0\gamma$  in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 855, p. 138762, 2024. <https://doi.org/10.1016/j.physletb.2024.138762>.



2024.138762.

- ATLAS Collaboration, “Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in  $WZ$  Production with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 133, no. 10, p. 101802, 2024. <https://doi.org/10.1103/PhysRevLett.133.101802>.
- ATLAS Collaboration, “Search for new particles in final states with a boosted top quark and missing transverse momentum in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 05, p. 263, 2024. [https://doi.org/10.1007/JHEP05\(2024\)263](https://doi.org/10.1007/JHEP05(2024)263).
- ATLAS Collaboration, “Search for a new  $Z'$  gauge boson via the  $pp \rightarrow W^\pm \rightarrow Z'\mu^\pm\nu \rightarrow \mu^\pm\mu^\mp\mu^\pm\nu$  process in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 110, no. 7, p. 072008, 2024. <https://doi.org/10.1103/PhysRevD.110.072008>.
- ATLAS Collaboration, “A search for top-squark pair production, in final states containing a top quark, a charm quark and missing transverse momentum, using the  $139\text{ fb}^{-1}$  of pp collision data collected by the ATLAS detector,” *JHEP*, vol. 07, p. 250, 2024. [https://doi.org/10.1007/JHEP07\(2024\)250](https://doi.org/10.1007/JHEP07(2024)250).
- ATLAS Collaboration, “Combination of searches for heavy spin-1 resonances using  $139\text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 04, p. 118, 2024. [https://doi.org/10.1007/JHEP04\(2024\)118](https://doi.org/10.1007/JHEP04(2024)118).
- ATLAS Collaboration, “Statistical Combination of ATLAS Run 2 Searches for Charginos and Neutralinos at the LHC,” *Phys. Rev. Lett.*, vol. 133, no. 3, p. 031802, 2024. <https://doi.org/10.1103/PhysRevLett.133.031802>.
- ATLAS Collaboration, “Combination of Measurements of the Top Quark Mass from Data Collected by the ATLAS and CMS Experiments at  $\sqrt{s} = 7$  and 8 TeV,” *Phys. Rev. Lett.*, vol. 132, no. 26, p. 261902, 2024. <https://doi.org/10.1103/PhysRevLett.132.261902>.
- ATLAS Collaboration, “Performance of the ATLAS forward proton Time-of-Flight detector in Run 2,” *JINST*, vol. 19, no. 05, p. P05054, 2024. <https://doi.org/10.1088/1748-0221/19/05/P05054>.
- ATLAS Collaboration, “ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM,” *JHEP*, vol. 05, p. 106, 2024. [https://doi.org/10.1007/JHEP05\(2024\)106](https://doi.org/10.1007/JHEP05(2024)106).
- ATLAS Collaboration, “Determination of the Relative Sign of the Higgs Boson Couplings to  $W$  and  $Z$  Bosons Using  $WH$  Production via Vector-Boson Fusion with the ATLAS

- Detector,” *Phys. Rev. Lett.*, vol. 133, no. 14, p. 141801, 2024. <https://doi.org/10.1103/PhysRevLett.133.141801>.
- ATLAS Collaboration, “Search for electroweak production of supersymmetric particles in final states with two  $\tau$ -leptons in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector,” *JHEP*, vol. 05, p. 150, 2024. [https://doi.org/10.1007/JHEP05\(2024\)150](https://doi.org/10.1007/JHEP05(2024)150).
  - ATLAS Collaboration, “Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment,” *Phys. Lett. B*, vol. 854, p. 138743, 2024. <https://doi.org/10.1016/j.physletb.2024.138743>.
  - ATLAS Collaboration, “A search for R-parity-violating supersymmetry in final states containing many jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 05, p. 003, 2024. [https://doi.org/10.1007/JHEP05\(2024\)003](https://doi.org/10.1007/JHEP05(2024)003).
  - ATLAS Collaboration, “Search for pair production of higgsinos in events with two Higgs bosons and missing transverse momentum in  $s = 13$  TeV pp collisions at the ATLAS experiment,” *Phys. Rev. D*, vol. 109, no. 11, p. 112011, 2024. <https://doi.org/10.1103/PhysRevD.109.112011>.
  - ATLAS Collaboration, “Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks in pp Collisions at  $s = 13$  TeV with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 132, no. 22, p. 221801, 2024. <https://doi.org/10.1103/PhysRevLett.132.221801>.
  - ATLAS Collaboration, “Search for new phenomena with top-quark pairs and large missing transverse momentum using 140 fb $^{-1}$  of pp collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 03, p. 139, 2024. [https://doi.org/10.1007/JHEP03\(2024\)139](https://doi.org/10.1007/JHEP03(2024)139).
  - ATLAS Collaboration, “Combination of searches for pair-produced leptoquarks at  $s = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 854, p. 138736, 2024. <https://doi.org/10.1016/j.physletb.2024.138736>.
  - ATLAS Collaboration, “The ATLAS trigger system for LHC Run 3 and trigger performance in 2022,” *JINST*, vol. 19, no. 06, p. P06029, 2024. <https://doi.org/10.1088/1748-0221/19/06/P06029>.
  - ATLAS Collaboration, “Measurement of the total and differential cross-sections of  $t\bar{t}W$  production in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 09, p. 075, 2024. [https://doi.org/10.1007/JHEP09\(2024\)075](https://doi.org/10.1007/JHEP09(2024)075).
  - ATLAS Collaboration, “Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS,” *Phys. Lett. B*, vol. 848, p. 138324, 2024. <https://doi.org/10.1016/j.physletb.2024.138324>.

[1016/j.physletb.2023.138324](https://doi.org/10.1016/j.physletb.2023.138324).

- ATLAS Collaboration, “Observation of  $WZ\gamma$  production in pp collisions at  $s = 13$  TeV with the ATLAS detector,” *Phys. Rev. Lett.*, vol. 132, no. 2, p. 021802, 2024. <https://doi.org/10.1103/PhysRevLett.132.021802>.
- ATLAS Collaboration, “Search for leptoquarks decaying into the  $b\tau$  final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 10, p. 001, 2023. [https://doi.org/10.1007/JHEP10\(2023\)001](https://doi.org/10.1007/JHEP10(2023)001).
- ATLAS Collaboration, “Search for Majorana neutrinos in same-sign WW scattering events from pp collisions at  $\sqrt{s} = 13$  TeV,” *Eur. Phys. J. C*, vol. 83, no. 9, p. 824, 2023. <https://doi.org/10.1140/epjc/s10052-023-11915-y>.
- ATLAS Collaboration, “Search for periodic signals in the dielectron and diphoton invariant mass spectra using  $139 \text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 10, p. 079, 2023. [https://doi.org/10.1007/JHEP10\(2023\)079](https://doi.org/10.1007/JHEP10(2023)079).
- ATLAS Collaboration, “Search for single production of vector-like T quarks decaying into Ht or Zt in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 08, p. 153, 2023. [https://doi.org/10.1007/JHEP08\(2023\)153](https://doi.org/10.1007/JHEP08(2023)153).
- ATLAS Collaboration, “Search for pairs of muons with small displacements in pp collisions at  $s = 13$  TeV with the ATLAS detector,” *Phys. Lett. B*, vol. 846, p. 138172, 2023. <https://doi.org/10.1016/j.physletb.2023.138172>.
- ATLAS Collaboration, “Search for a new pseudoscalar decaying into a pair of muons in events with a top-quark pair at  $s = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 108, no. 9, p. 092007, 2023. <https://doi.org/10.1103/PhysRevD.108.092007>.
- ATLAS Collaboration, “Performance of the reconstruction of large impact parameter tracks in the inner detector of ATLAS,” *Eur. Phys. J. C*, vol. 83, no. 11, p. 1081, 2023. <https://doi.org/10.1140/epjc/s10052-023-12024-6>.
- ATLAS Collaboration, “Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS,” *JHEP*, vol. 07, p. 234, 2023. [https://doi.org/10.1007/JHEP07\(2023\)234](https://doi.org/10.1007/JHEP07(2023)234).
- ATLAS Collaboration, “Test of CP-invariance of the Higgs boson in vector-boson fusion production and in its decay into four leptons,” *JHEP*, vol. 05, p. 105, 2024. [https://doi.org/10.1007/JHEP05\(2024\)105](https://doi.org/10.1007/JHEP05(2024)105).
- ATLAS Collaboration, “Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Eur. Phys. J. C*, vol. 83, no. 12, p. 1164, 2023.

<https://doi.org/10.1140/epjc/s10052-023-12021-9>.

- ATLAS Collaboration, “Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector,” *Phys. Rev. Lett.*, vol. 131, no. 15, p. 151902, 2023. <https://doi.org/10.1103/PhysRevLett.131.151902>.
- ATLAS Collaboration, “Integrated and differential fiducial cross-section measurements for the vector boson fusion production of the Higgs boson in the  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  decay channel at 13 TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 108, no. 7, p. 072003, 2023. <https://doi.org/10.1103/PhysRevD.108.072003>.
- ATLAS Collaboration, “Search for top-philic heavy resonances in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Eur. Phys. J. C*, vol. 84, no. 2, p. 157, 2024. <https://doi.org/10.1140/epjc/s10052-023-12318-9>.
- ATLAS Collaboration, “New techniques for jet calibration with the ATLAS detector,” *Eur. Phys. J. C*, vol. 83, no. 8, p. 761, 2023. <https://doi.org/10.1140/epjc/s10052-023-11837-9>.
- ATLAS Collaboration, “Measurement of the Sensitivity of Two-Particle Correlations in pp Collisions to the Presence of Hard Scatterings,” *Phys. Rev. Lett.*, vol. 131, no. 16, p. 162301, 2023. <https://doi.org/10.1103/PhysRevLett.131.162301>.
- ATLAS Collaboration, “Observation of four-top-quark production in the multilepton final state with the ATLAS detector,” *Eur. Phys. J. C*, vol. 83, no. 6, p. 496, 2023. <https://doi.org/10.1140/epjc/s10052-023-11573-0> [Erratum: *Eur. Phys. J. C* 84, 156 (2024)].
- ATLAS Collaboration, “Comparison of inclusive and photon-tagged jet suppression in 5.02 TeV Pb+Pb collisions with ATLAS,” *Phys. Lett. B*, vol. 846, p. 138154, 2023. <https://doi.org/10.1016/j.physletb.2023.138154>.
- ATLAS Collaboration, “Search for excited  $\tau$ -leptons and leptoquarks in the final state with  $\tau$ -leptons and jets in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 06, p. 199, 2023. [https://doi.org/10.1007/JHEP06\(2023\)199](https://doi.org/10.1007/JHEP06(2023)199).
- ATLAS Collaboration, “A precise measurement of the Z-boson double-differential transverse momentum and rapidity distributions in the full phase space of the decay leptons with the ATLAS experiment at  $\sqrt{s} = 8$  TeV,” *Eur. Phys. J. C*, vol. 84, no. 3, p. 315, 2024. <https://doi.org/10.1140/epjc/s10052-024-12438-w>.
- ATLAS Collaboration, “Measurements of the suppression and correlations of dijets in Xe+Xe collisions at  $s_{NN} = 5.44$  TeV,” *Phys. Rev. C*, vol. 108, no. 2, p. 024906, 2023. <https://doi.org/10.1103/PhysRevC.108.024906>.

- ATLAS Collaboration, “Measurement of the production of a  $W$  boson in association with a charmed hadron in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *Phys. Rev. D*, vol. 108, p. 032012, 2023. <https://doi.org/10.1103/PhysRevD.108.032012>.
- ATLAS Collaboration, “Search for lepton-flavour violation in high-mass dilepton final states using  $139 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector,” *JHEP*, vol. 23, p. 082, 2020. [https://doi.org/10.1007/JHEP10\(2023\)082](https://doi.org/10.1007/JHEP10(2023)082).

# Appendices

# Appendix A

## Additional data for Electron Reconstruction Efficiencies Studies

This appendix corresponds to the chapter 4 of the thesis.

### Datasets details to perform the measurements

---

| Datasets             | Signal $Z \rightarrow ee$                                                                                                                                                                                                                                                                                                                                                |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data Samples (rel22) | <code>data15_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp15.v01.p5057</code><br><code>data16_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp16.v01.p5057</code><br><code>data17_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp17.v02.p5057</code><br><code>data18_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp18.v01.p4926</code> |
| MC Samples (rel22)   | <code>mc20_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DAOD.EGAM1.e3601.s3681.r13167.p4940</code><br><code>mc20_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DAOD.EGAM1.e3601.s3681.r13144.p4940</code><br><code>mc20_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DAOD.EGAM1.e3601.s3681.r13145.p4940</code>                          |

Table A.1: The datasets used for the electron reconstruction efficiency measurements with data and MC for complete Run2, i.e. for the years 2015+2016, 2017, and 2018

| Datasets           | Signal $Z \rightarrow ee$                                                                                                  |
|--------------------|----------------------------------------------------------------------------------------------------------------------------|
| Data Samples (R21) | <code>data18_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp18.v01.p4332</code>                                    |
| MC Samples (R21)   | <code>mc16_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DAOD.EGAM1.e3601.e5984.s3126.r10724.r10726.p4323</code> |
| Data Samples (R22) | <code>data18_13TeV.periodAllYear.physics.Main.PhyCont.DAOD.EGAM1.grp18.v01.p4926</code>                                    |
| MC Samples (R22)   | <code>mc20_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.deriv.DAOD.EGAM1.e3601.s3681.r13145.p4940</code>              |

Table A.2: The datasets used for comparing rel21 and rel22 efficiencies and scale factors.

| Datasets           | Signal $Z \rightarrow ee$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|--------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data Samples (R22) | data22_13p6TeV.00429027.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429142.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429470.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429606.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429612.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429658.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429697.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429716.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429782.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429929.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429940.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00429993.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430036.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430183.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430336.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430183.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430336.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430341.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430536.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430542.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430580.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430648.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267<br>data22_13p6TeV.00430702.physics_Main.deriv.DAOD_EGAM1.r13928.p5279.p5267 |
| MC Samples (R22)   | mc21_13p6TeV.601189.PbPy8EG_AZNLO_Zee.deriv.DAOD_EGAM1.e8453.e8455.s3873.s3874.r13829.r13831.p5273/                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |

Table A.3: The datasets used to measure early Run 3 electron reconstruction efficiency and scale factors.



# Efficiency and ScaleFactor plots for all $E_T$ bins with re-processed Run2 data for year 2015-16

---

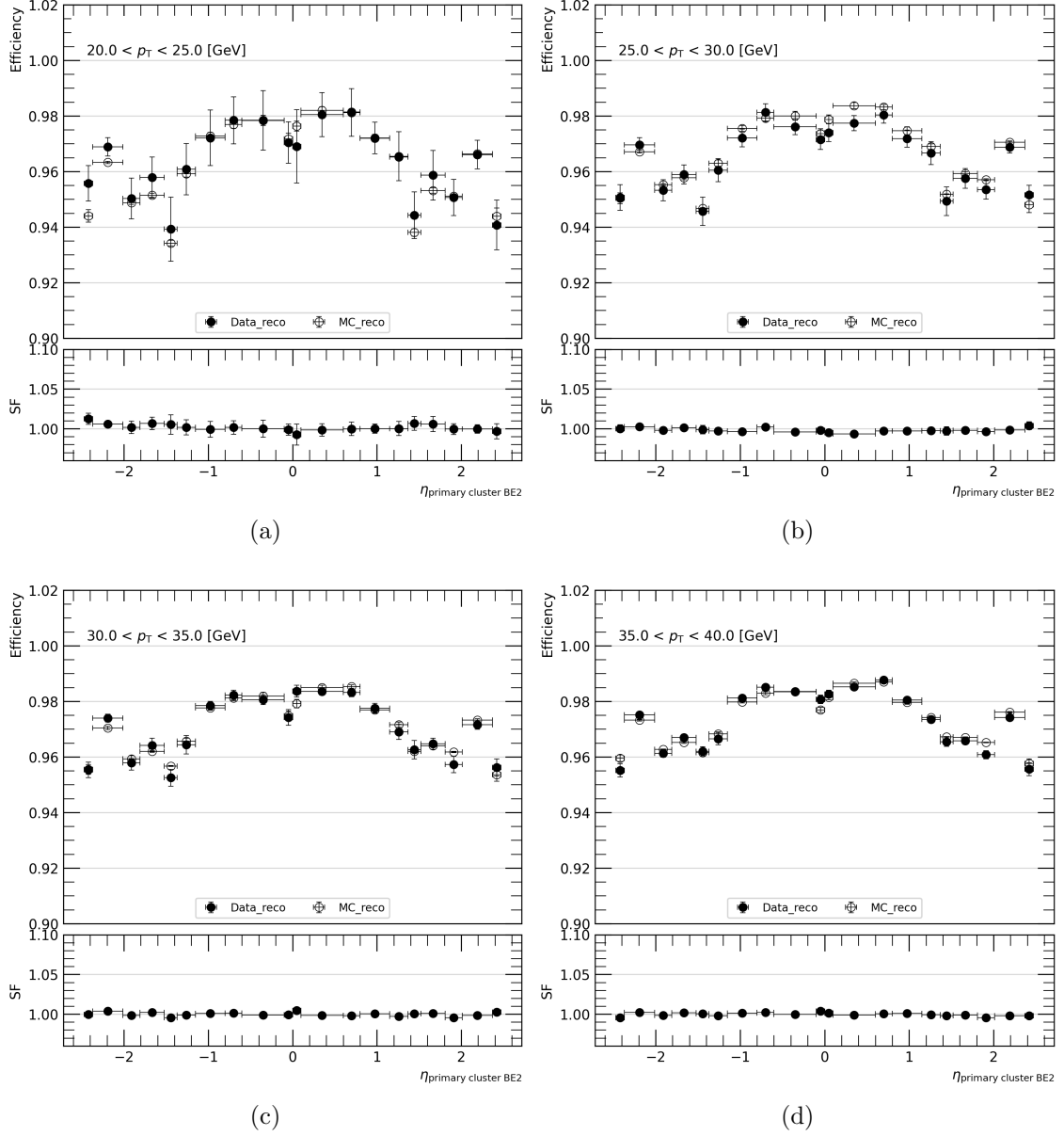


Figure A.1: The figures illustrate a comparison between data efficiency and MC efficiency for the years 2015 and 2016, respectively. They cover bins from  $20 < E_T < 25\text{GeV}$  up to  $35 < E_T < 40\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

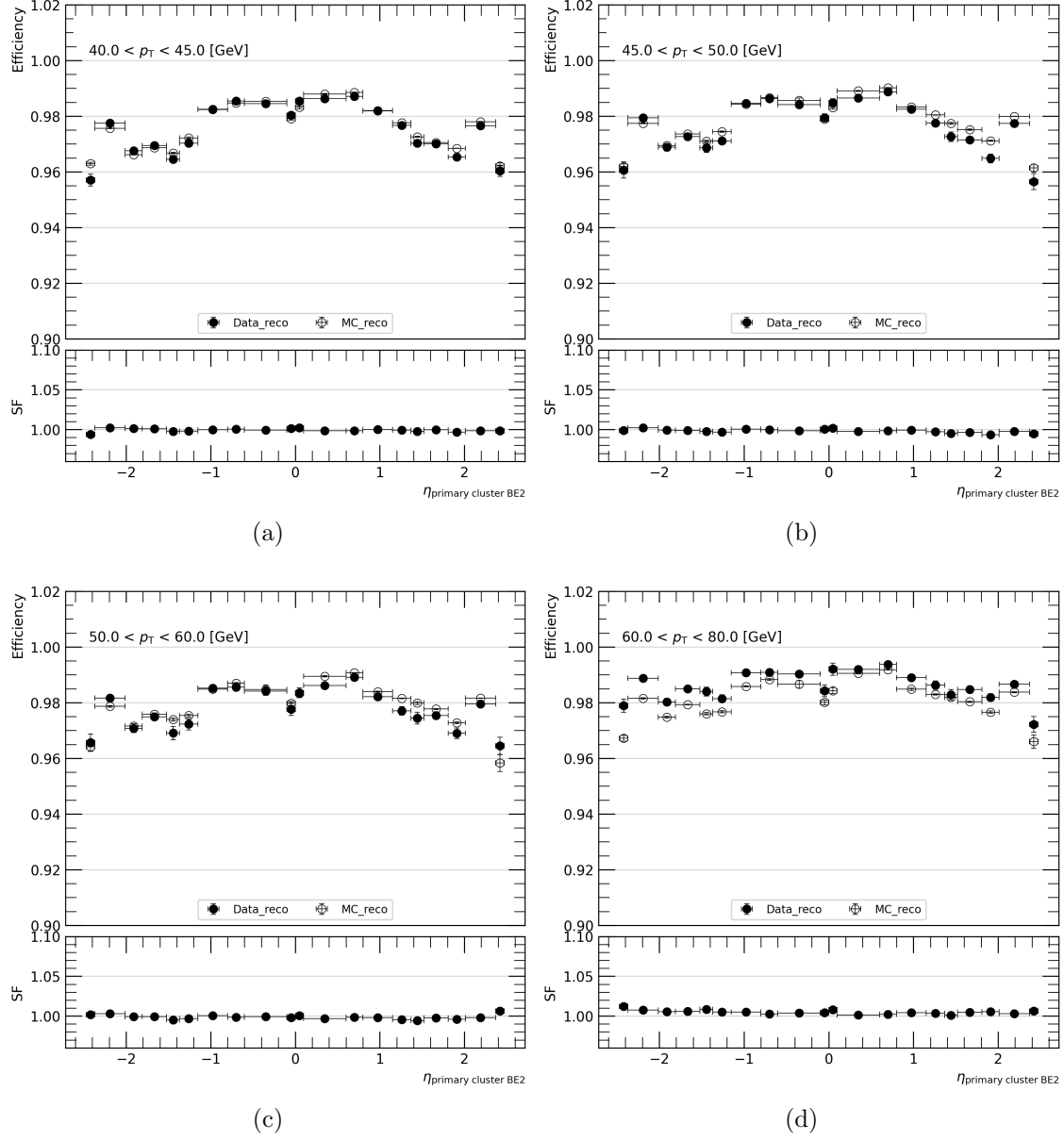


Figure A.2: The figures illustrate a comparison between data efficiency and MC efficiency for the years 2015 and 2016, respectively. They cover bins from  $40 < E_T < 45\text{GeV}$  up to  $60 < E_T < 80\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

# Efficiency and ScaleFactor plots for all $E_T$ bins with re-processed Run2 data for year 2017

---

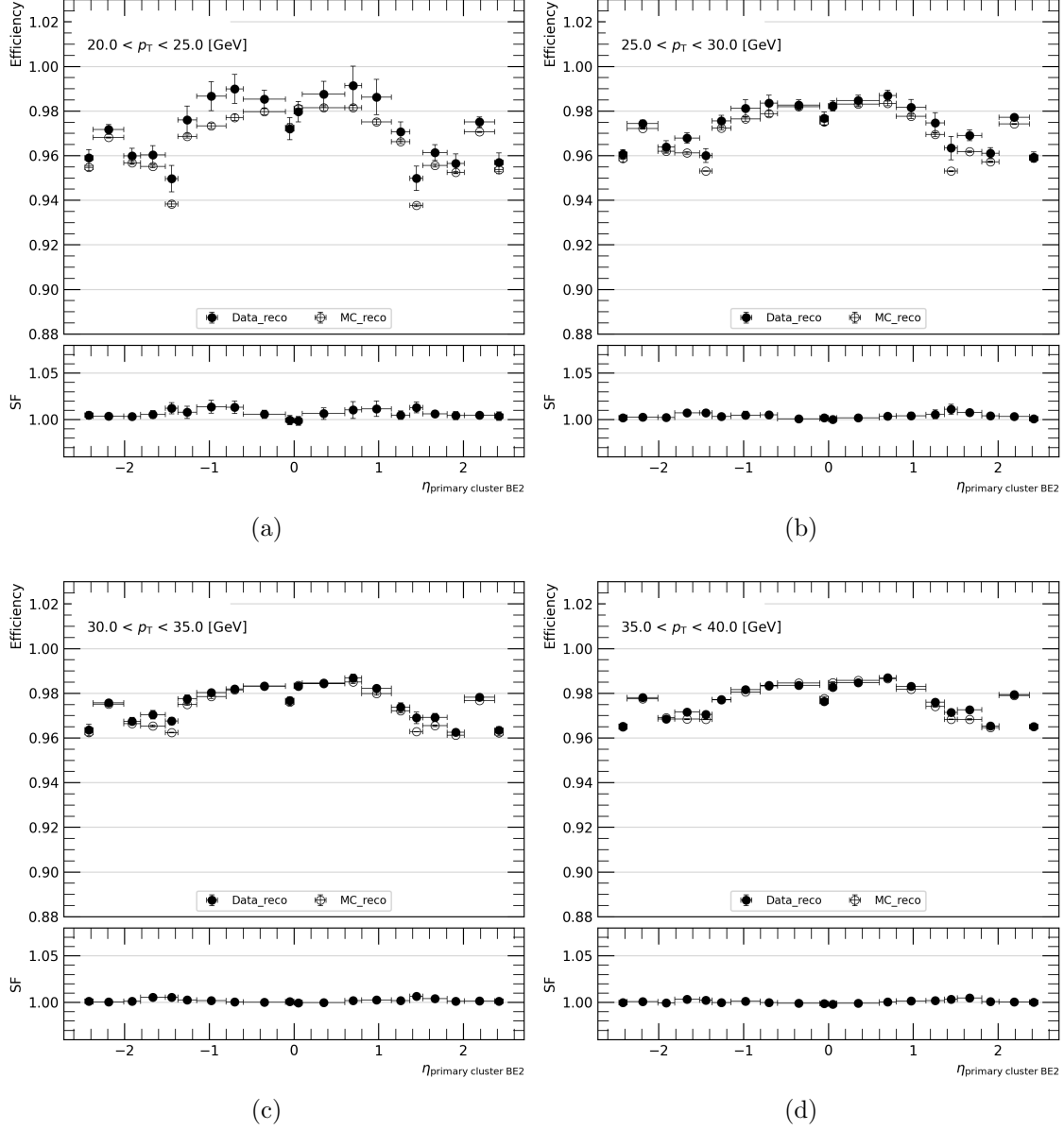


Figure A.3: The figures illustrate a comparison between data efficiency and MC efficiency for 2017. They cover bins from  $20 < E_T < 25\text{GeV}$  up to  $35 < E_T < 40\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

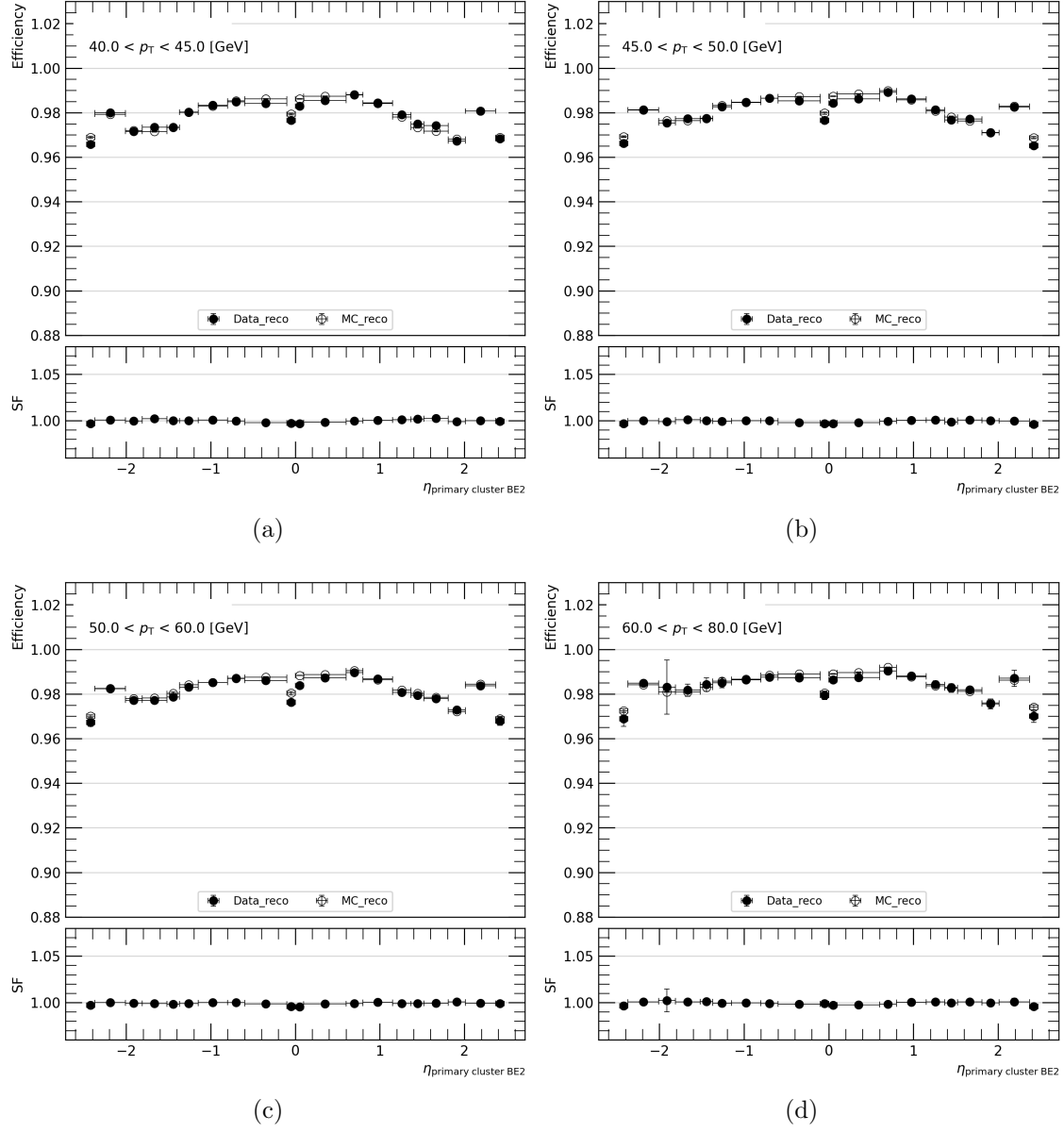


Figure A.4: The figures illustrate a comparison between data efficiency and MC efficiency for 2017. They cover bins from  $40 < E_T < 45\text{GeV}$  up to  $60 < E_T < 80\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

# Efficiency and ScaleFactor plots for all $E_T$ bins with re-processed Run2 data for year 2018

---

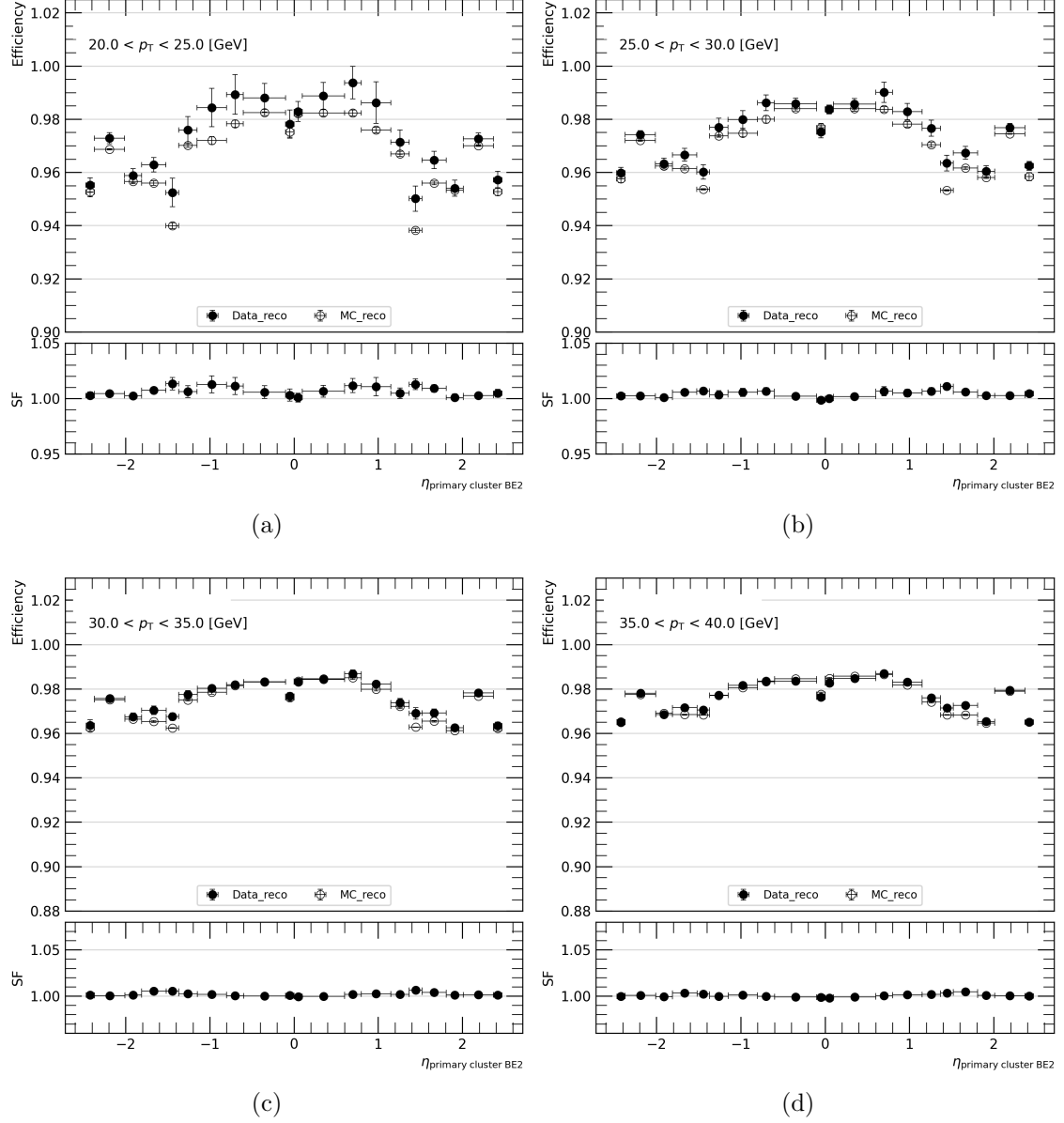


Figure A.5: The figures illustrate a comparison between data efficiency and MC efficiency for 2018. They cover bins from  $20 < E_T < 25\text{GeV}$  up to  $35 < E_T < 40\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

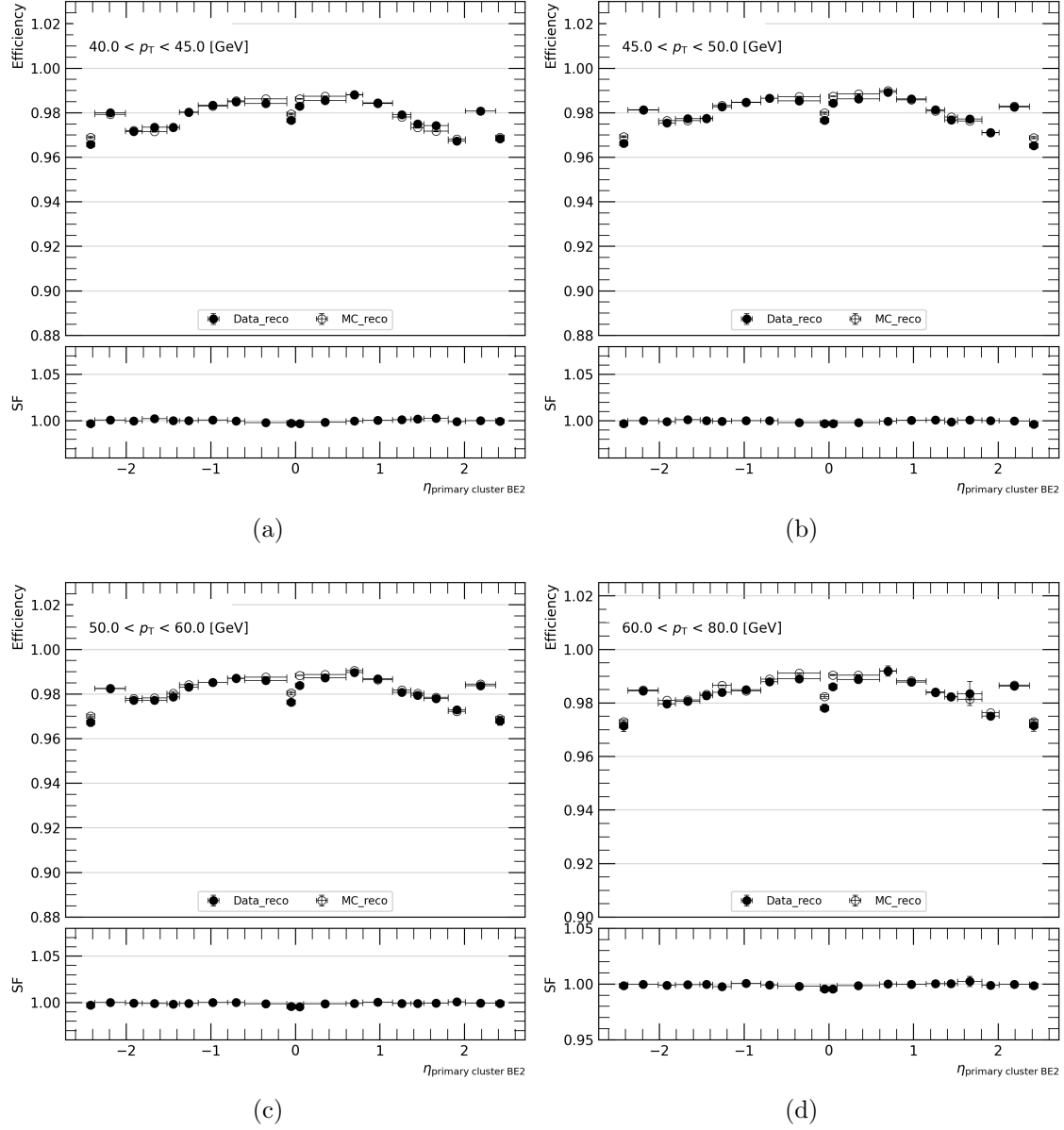


Figure A.6: The figures illustrate a comparison between data efficiency and MC efficiency for 2018. They cover bins from  $40 < E_T < 25\text{GeV}$  up to  $60 < E_T < 80\text{GeV}$ . In the lower panels, the Scale Factors for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

# Efficiency and ScaleFactor plots for all $E_T$ bins with early first year Run3 data

---

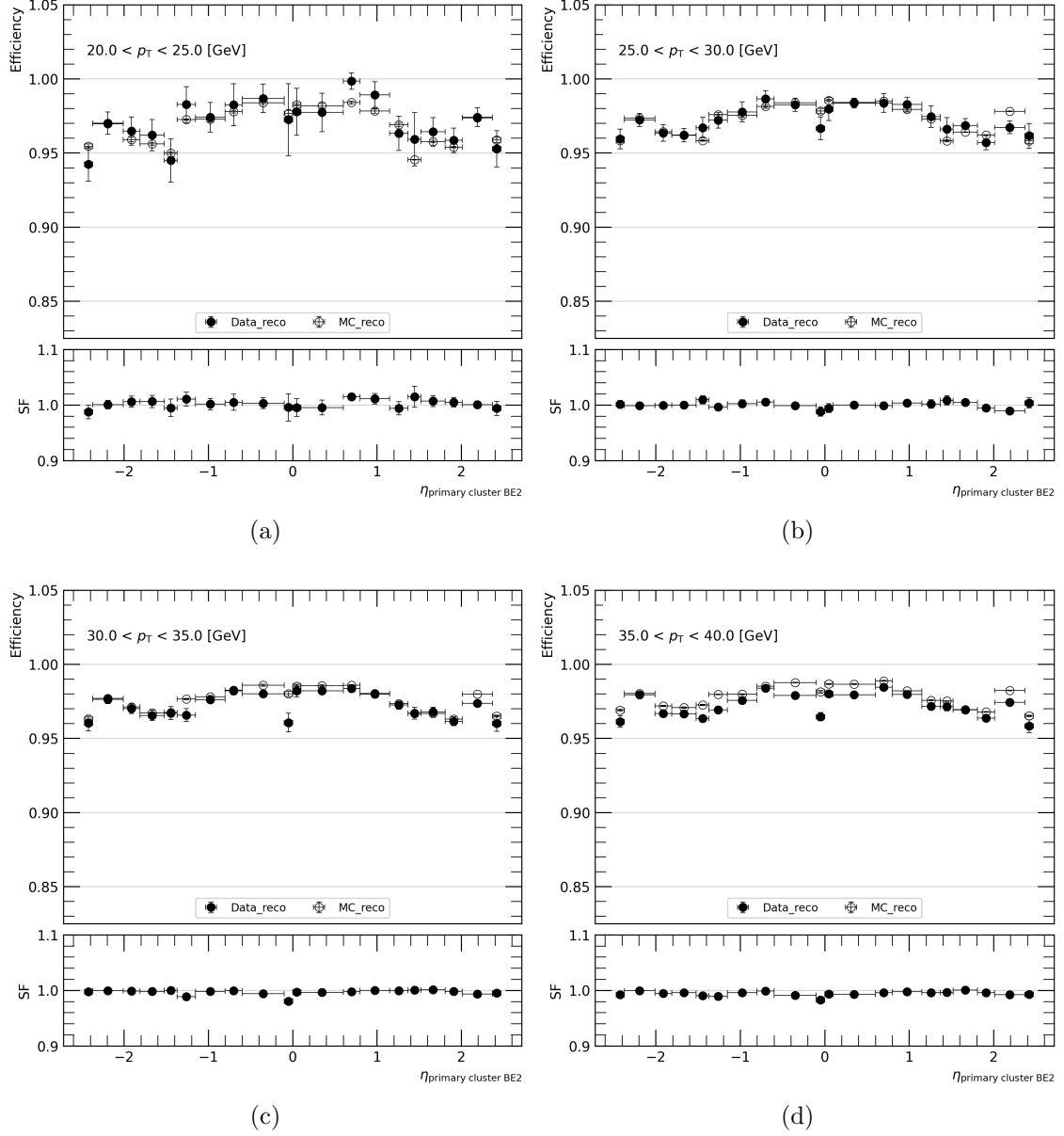


Figure A.7: The figures illustrate a comparison between data efficiency and MC efficiency for the early first year Run 3. They cover bins from  $20 < E_T < 25\text{GeV}$  up to  $35 < E_T < 40\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.

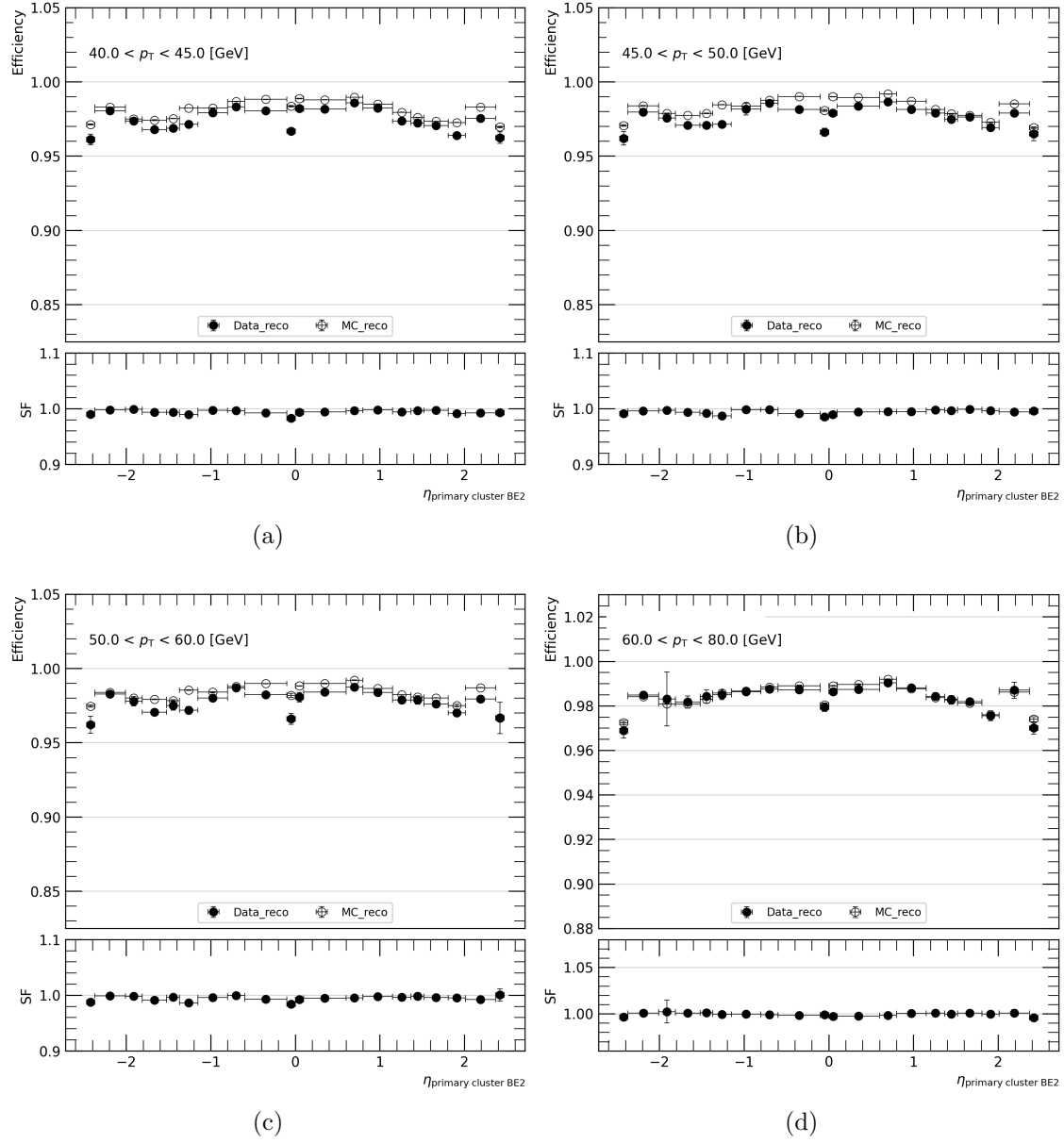


Figure A.8: The figures illustrate a comparison between data efficiency and MC efficiency for the early first year Run 3. They cover bins from  $40 < E_T < 45\text{GeV}$  up to  $60 < E_T < 80\text{GeV}$ . In the lower panels, the **Scale Factors** for these bins are displayed. The error bars indicate total uncertainties, which include both statistical and systematic components.



# Appendix B

## Additional data for Fake Tracks Measurements Studies

This appendix corresponds to the chapter 5 of the thesis.

### Datasets details to perform the measurements

---

The analysis was conducted using the Rel22 reprocessed  $pp$  collision data, recorded by the ATLAS detector from 2015 to 2018. This dataset has a total integrated luminosity corresponding to  $140 \text{ fb}^{-1}$ . The Data files used in the analysis are:

Table B.1: Data Samples used in the Fake Track Studies Measurements

| Year | Data Set                                                                                |
|------|-----------------------------------------------------------------------------------------|
| 2018 | data18_13TeV: data18_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_IDTIDE.repro26_v01/ |
| 2017 | data17_13TeV: data17_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_IDTIDE.repro26_v01/ |
| 2016 | data16_13TeV: data16_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_IDTIDE.repro26_v01/ |
| 2015 | data15_13TeV: data15_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_IDTIDE.repro26_v01/ |

Table B.2: Monte Carlo simulated samples used in the Fake Track Studies Measurements

| Monte Carlo Sample                                                                                        |
|-----------------------------------------------------------------------------------------------------------|
| mc20_13TeV.364704.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ4WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13458.r13459 |
| mc20_13TeV.364704.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ4WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13460.r13459 |
| mc20_13TeV.364704.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ4WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13461.r13459 |
| mc20_13TeV.364705.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ5WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13458.r13459 |
| mc20_13TeV.364705.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ5WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13460.r13459 |
| mc20_13TeV.364705.Pythia8EvtGen_A14NNPDF23LO_jetjet_JZ5WithSW.merge.DAOD_IDTIDE.e7142.s3681.r13461.r13459 |

# Fraction of fake tracks for TightPrimaryWP

## Distributions for TightPrimaryWP after pre-selection

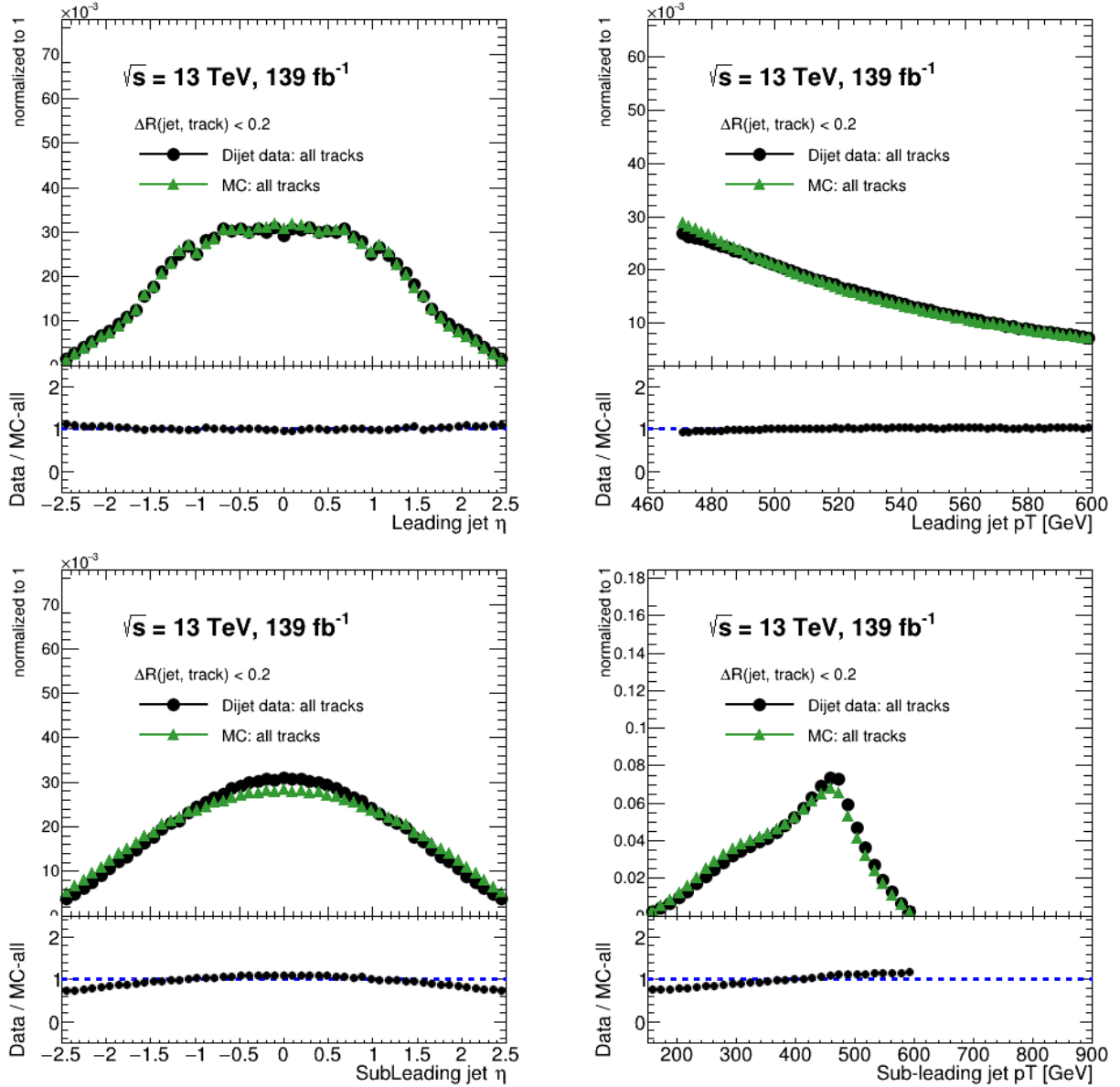


Figure B.1: Distributions for TightPrimaryWP after the pre-selection. The top left and bottom left plots show the leading and sub-leading jet  $\eta$  distributions, respectively. The top right and bottom right plots show the leading and sub-leading jet  $p_T$  distributions, respectively. Black dots represent data points, and green up-triangles represent MC for all tracks. The ratio plots beneath each distribution compare the data to MC, with the last bin in each distribution including overflow events.

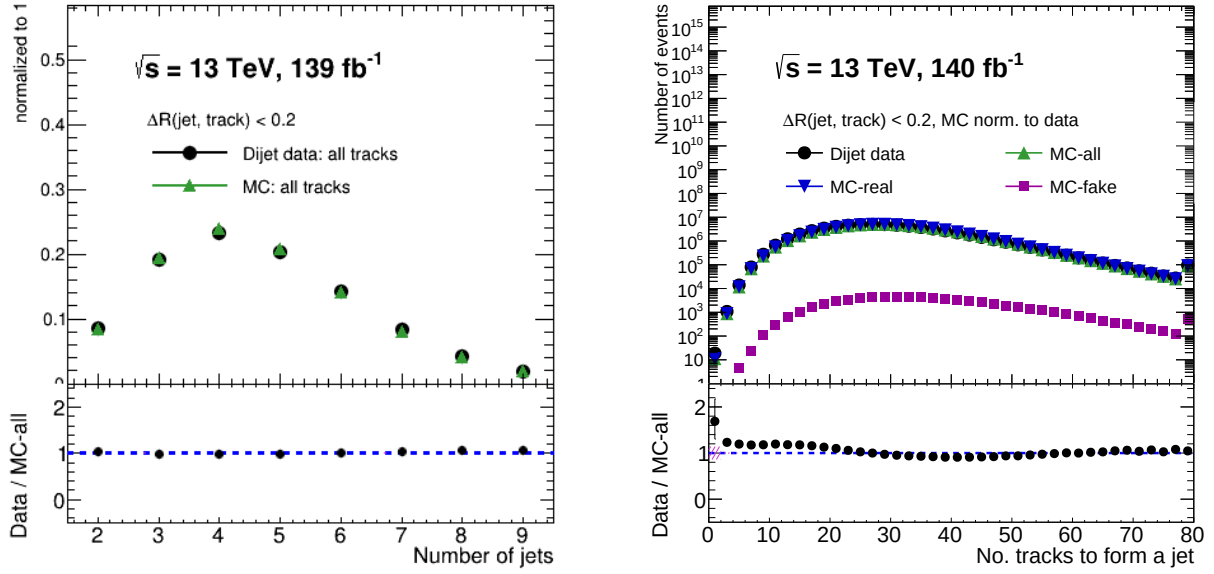


Figure B.2: Distributions for `TightPrimaryWP` following the pre-selection. The plot on the left displays the number of jets, while the right plot illustrates the number of tracks in the jet. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events.

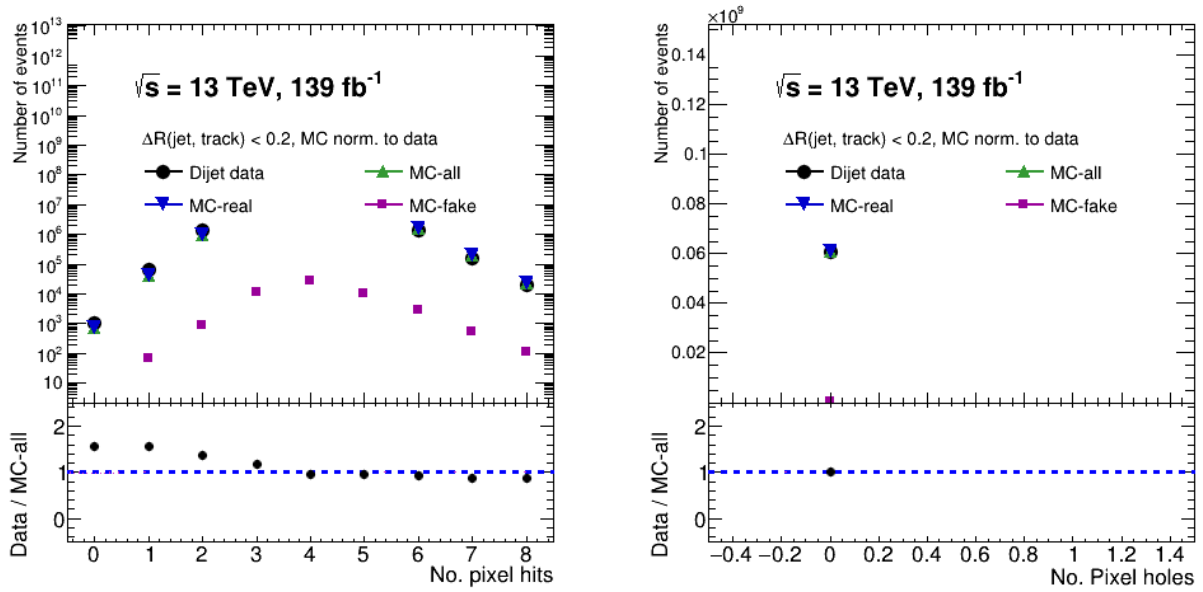


Figure B.3: Distributions for `TightPrimaryWP` after the pre-selection. The left plot shows the distribution of the number of pixel hits, while the right plot shows the distribution of the number of pixel holes. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events.

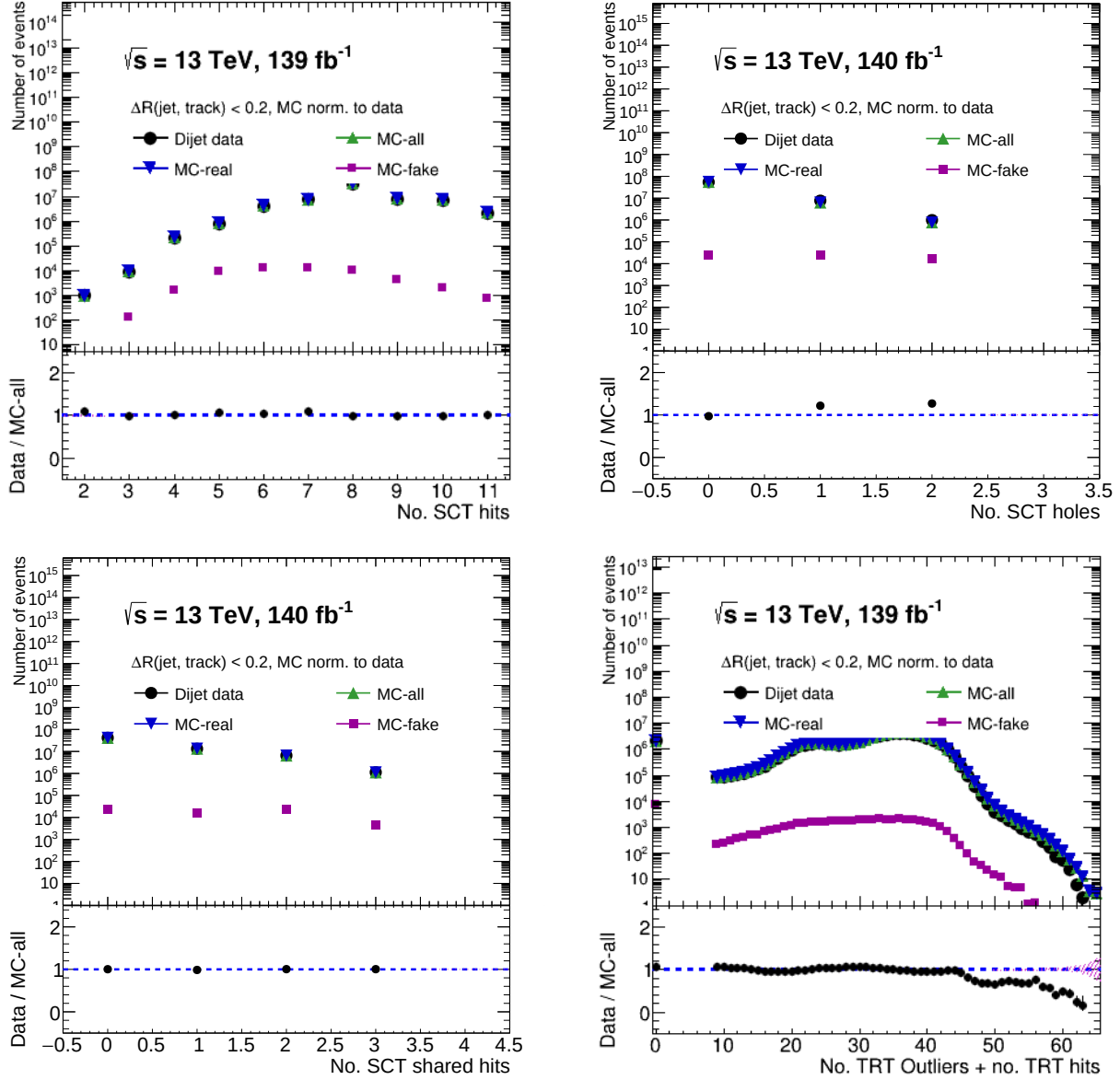


Figure B.4: Distributions for `TightPrimaryWP` after the pre-selection. The top left plot shows the distribution of the number of SCT hits, the top right plot shows the distribution of the number of SCT holes, and the bottom left plot shows the distribution of the number of SCT shared hits. The bottom right plot shows the distribution of the combined number of TRT outliers and TRT hits. The results are shown for data (black dots), and MC contribution is either inclusively or split into separate real/fake track components. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in both distributions including overflow events.

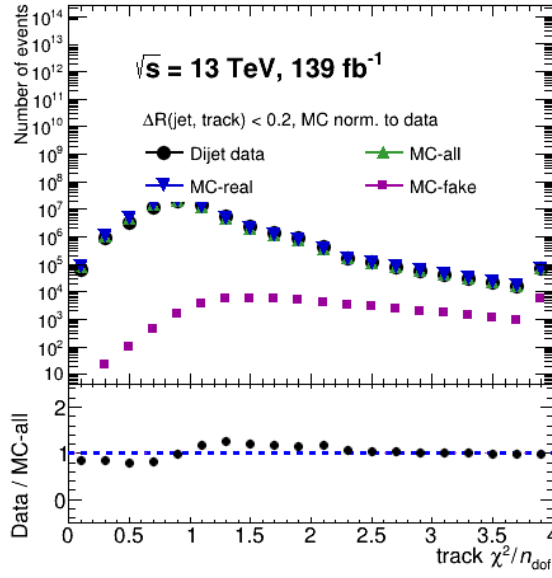


Figure B.5: Distributions for TightPrimaryWP of the track  $\chi^2/\text{DOF}$  variable after pre-selection, shown for both data and MC simulation. The final bin accounts for overflow. The hashed magenta region in the lower panel indicates the MC statistical uncertainty.

## Distributions of the variables for TightPrimaryWP used to define the CR

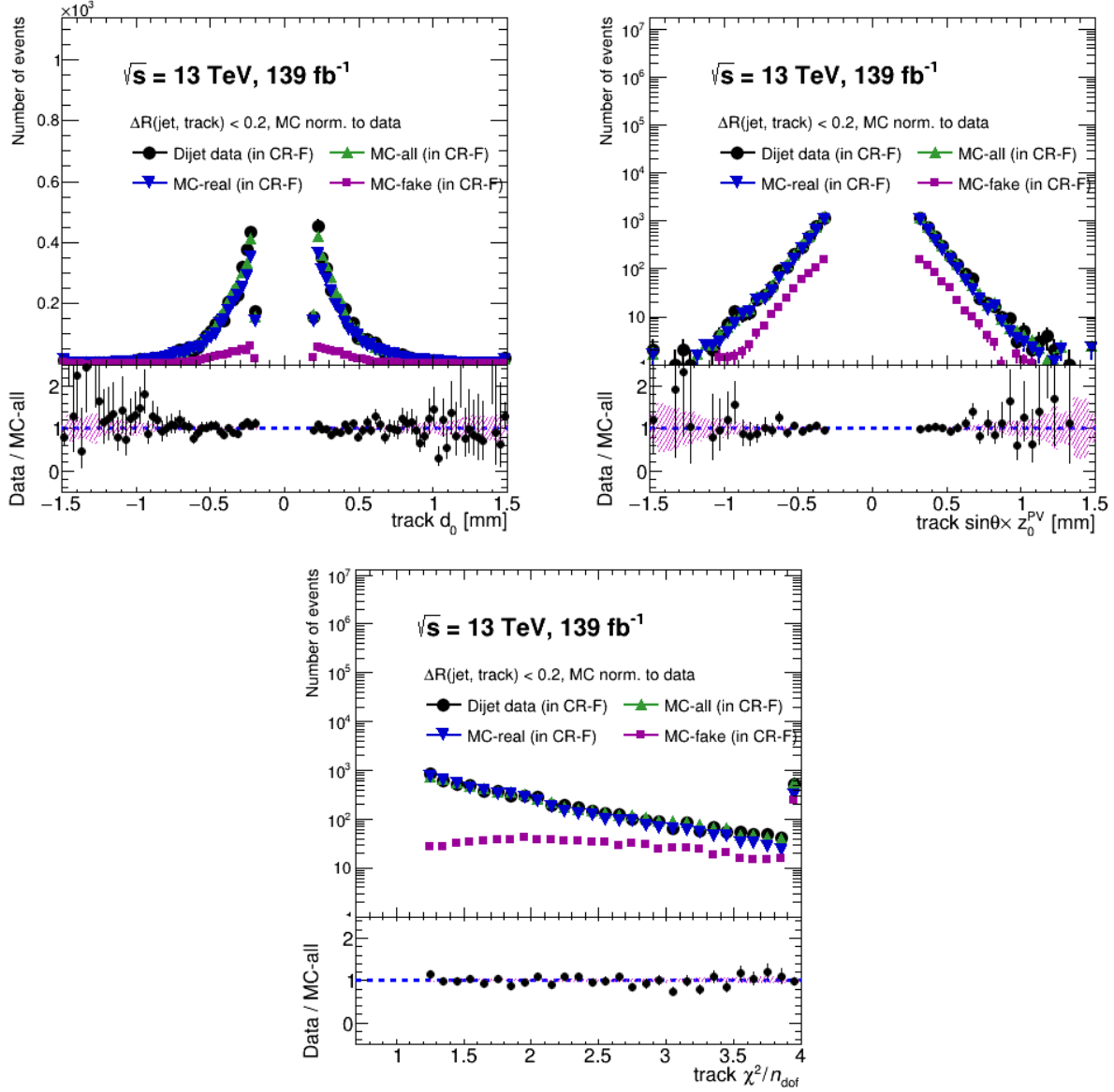


Figure B.6: Distributions for TightPrimaryWP defined fake enriched CR. The top left plot shows the distribution of the track transverse impact parameter ( $d_0$ ), and the top right plot shows the distribution of sin of the theta angle multiplied by the track longitudinal impact parameter computed with respect to the primary vertex. The bottom plot shows the distribution of the track  $\chi^2/\text{DOF}$ . The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalized to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events.

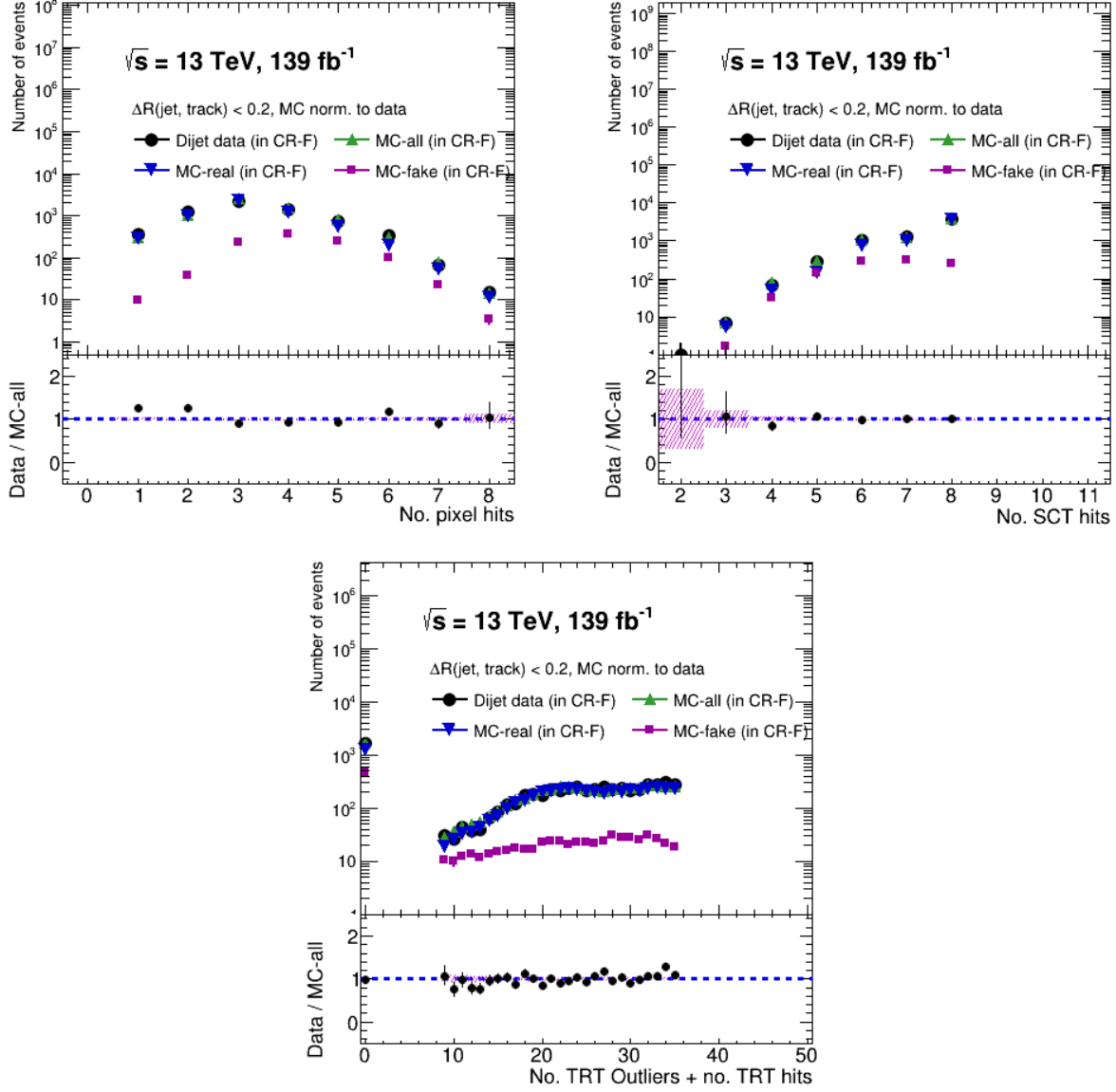


Figure B.7: Distributions for `TightPrimaryWP` defined fake enriched CR. The top left plot shows the distribution of the Number of pixel hits, and the top right plot shows the distribution of the Number of SCT hits. The bottom plot shows the distribution of the Number of TRT Outliers plus TRT hits. The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalized to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events.

## Results after fitting the distributions for TightPrimaryWP

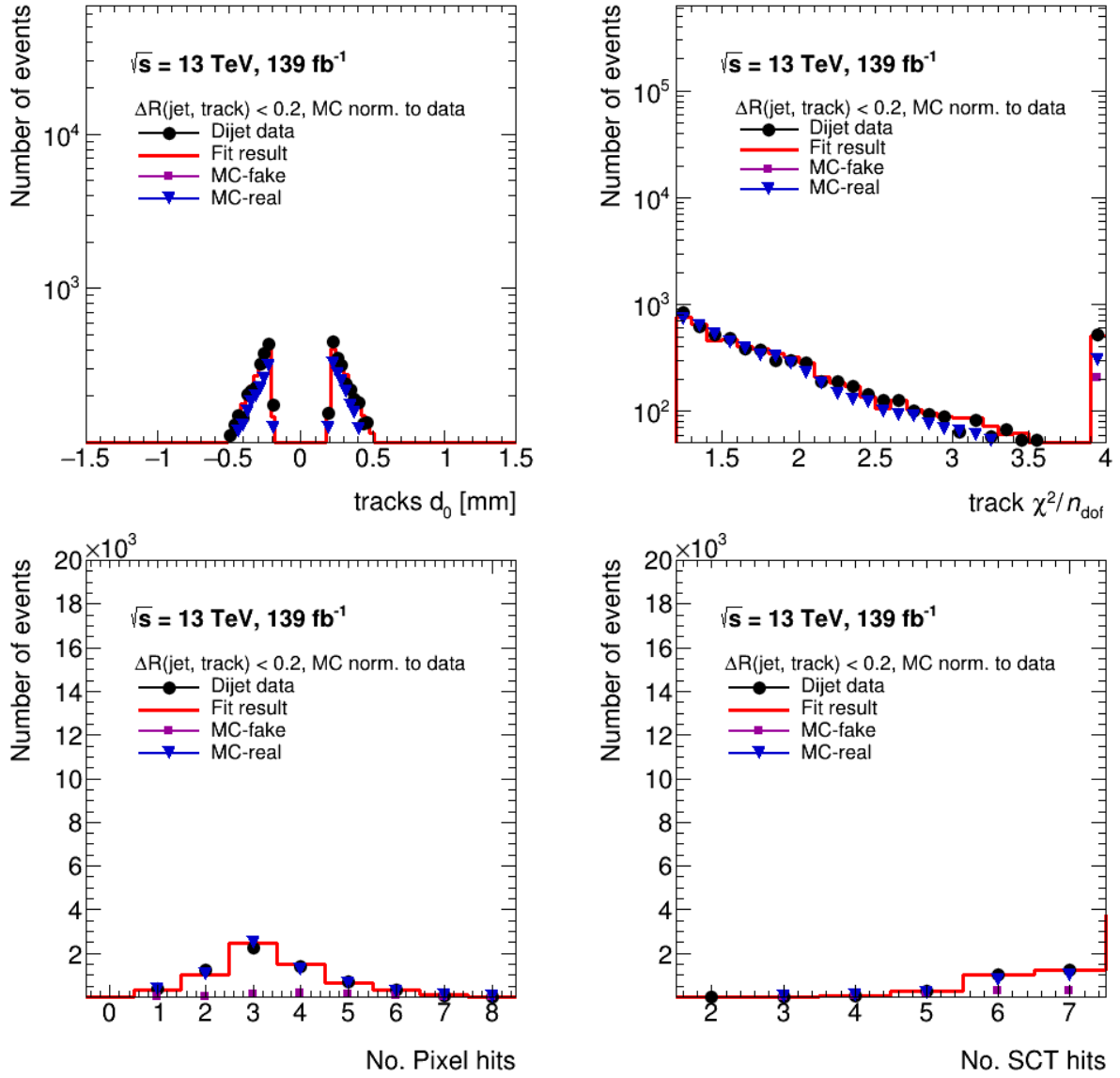


Figure B.8: The good performance of the fit (red line) in the CR enriched in fake tracks. Data (back dots), MC real tracks (blue down-triangles) and MC fake tracks (magenta squares) distributions are also shown. The last bin includes overflow. Only the statistical uncertainties are considered.



## Fraction of fake tracks results for TightPrimaryWP

Figure B.8 illustrates the fitting results of the distribution for some variables, specifically for the TightPrimaryWP. The fit results match the observed data within the **CR**. A detailed summary of the fitted results for the TightPrimaryWP is shown in Table no. B.3. The fitted fraction of **FT** in the **CR** ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) is observed to vary between 9% to 16%, depending on the fitting variable.

| Selected variable            | $f_{\text{CR}}^{\text{fakeTrk}} \text{ MLE}$ | $f_{\text{CR}}^{\text{fakeTrk}} \text{ Toys}$ | $f_{\text{CR}}^{\text{fakeTrk}} \text{ Histo } \chi^2/\text{DOF}$    |
|------------------------------|----------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------|
| track $\chi^2/\text{DOF}$    | $0.13222 \pm 0.01382$                        | $0.13432 \pm 0.01442$                         | $0.13352 \begin{smallmatrix} +0.01442 \\ -0.01442 \end{smallmatrix}$ |
| $n_{\text{SCT hits}}$        | $0.14812 \pm 0.01522$                        | $0.16252 \pm 0.01472$                         | $0.16132 \begin{smallmatrix} +0.01522 \\ -0.01512 \end{smallmatrix}$ |
| $n_{\text{SCT holes}}$       | $0.16202 \pm 0.01462$                        | $0.17452 \pm 0.01422$                         | $0.17522 \begin{smallmatrix} +0.01432 \\ -0.01422 \end{smallmatrix}$ |
| $n_{\text{SCT shared hits}}$ | $0.08822 \pm 0.02172$                        | $0.12112 \pm 0.02182$                         | $0.11792 \begin{smallmatrix} +0.02172 \\ -0.02162 \end{smallmatrix}$ |

Table B.3: TightPrimaryWP. The fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) along with the corresponding statistical uncertainty after fitting the chosen distributions. The outcomes of the 1000 toy experiments and the minima of the  $\chi^2/n_{\text{DOF}}$  from the data and MC histograms of these variables are presented.

Figure B.9 shows a comparison between the data and the **MC** simulation using a  $\chi^2$  test for the TightPrimaryWP selection.

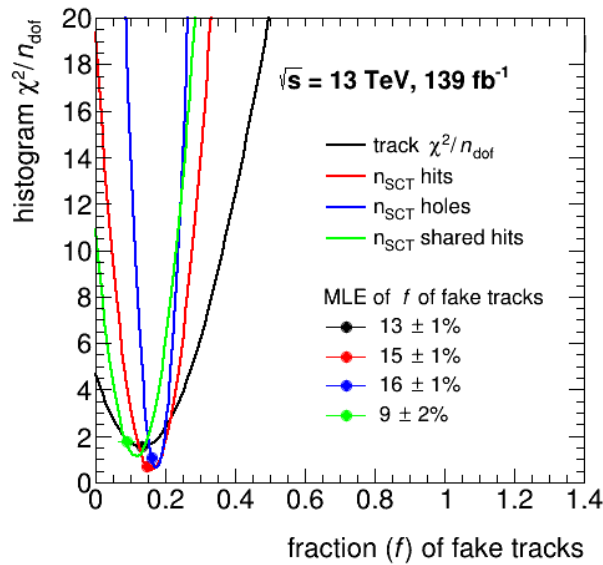


Figure B.9: TightPrimaryWP. Data & MC simulation  $\chi^2/\text{DOF}$  when varying the fraction of fake tracks “f” in the CR. The fit results (Maximum Likelihood Estimation of the fraction of fake tracks) are also shown with coloured dots.

## Fraction of fake tracks results for different bins of $< \mu >$

For  $< \mu > < 25$

Table B.4: Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the LooseWP.

|                                                                | $N_{\text{tracks}}^{\text{data}}$ | $\frac{F_{\text{trk}}}{R_{\text{trk}}} [\%]$ | $\varepsilon$ data [%] | $\varepsilon$ MC [%] |
|----------------------------------------------------------------|-----------------------------------|----------------------------------------------|------------------------|----------------------|
| pre-selection                                                  | 15221735                          | 0.098                                        | -                      | -                    |
| + $ d_0  > 0.2$                                                | 118497                            | 3.170                                        | 0.8                    | 0.8                  |
| + $\sin \theta \times  z_{PV}^0  > 0.3$                        | 8104                              | 6.291                                        | 6.8                    | 6.4                  |
| + track $\chi^2/\text{DOF} \geq 1.2$                           | 3753                              | 14.046                                       | 46.3                   | 45.1                 |
| + $n_{\text{SCT}} < 9$ , + $n_{\text{Pixel}} > 0$              | 2510                              | 18.555                                       | 66.9                   | 67.7                 |
| + $(n_{\text{TRT}} + n_{\text{TRT Outliers}}) < 36$ (final CR) | 2128                              | 20.746                                       | 84.8                   | 85.5                 |

Table B.5: LooseWP. Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the  $\chi^2/\text{DOF}$  of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column.

| Selected variable            | $f_{\text{CR MLE}}^{\text{fakeTrk}}$ | $f_{\text{CR Toys}}^{\text{fakeTrk}}$ | $f_{\text{CR Histo } \chi^2/\text{DOF}}^{\text{fakeTrk}}$ |
|------------------------------|--------------------------------------|---------------------------------------|-----------------------------------------------------------|
| track $\chi^2/\text{DOF}$    | $0.11312 \pm 0.02842$                | $0.11562 \pm 0.02942$                 | $0.10562^{+0.02762}_{-0.02752}$                           |
| $n_{\text{SCT}}$ hits        | $0.21232 \pm 0.02982$                | $0.20072 \pm 0.02852$                 | $0.20002^{+0.02752}_{-0.02722}$                           |
| $n_{\text{SCT}}$ holes       | $0.20732 \pm 0.02542$                | $0.18712 \pm 0.02512$                 | $0.18692^{+0.02552}_{-0.02522}$                           |
| $n_{\text{SCT}}$ shared hits | $0.15322 \pm 0.03302$                | $0.16172 \pm 0.03312$                 | $0.15592^{+0.03402}_{-0.03362}$                           |

Table B.6: **LooseWP**. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the fit of the selected distributions.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>Data | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>MC | Relative difference wrt MC |
|------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------|
| track $\chi^2/\text{DOF}$    | 0.00071                                       | 0.000975                                    | -0.27                      |
| $n_{\text{SCT}}$ hits        | 0.00134                                       | 0.000975                                    | 0.37                       |
| $n_{\text{SCT}}$ holes       | 0.00131                                       | 0.000975                                    | 0.34                       |
| $n_{\text{SCT}}$ shared hits | 0.00096                                       | 0.000975                                    | -0.01                      |

Table B.7: **LooseWP**. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the toys experiment.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>Data | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>MC | Relative difference wrt MC |
|------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------|
| track $\chi^2/\text{DOF}$    | 0.00073                                       | 0.00097                                     | -0.25                      |
| $n_{\text{SCT}}$ hits        | 0.00126                                       | 0.00097                                     | 0.30                       |
| $n_{\text{SCT}}$ holes       | 0.00118                                       | 0.00097                                     | 0.21                       |
| $n_{\text{SCT}}$ shared hits | 0.00102                                       | 0.00097                                     | 0.04                       |

Table B.8: **LooseWP**. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the histogram  $\chi^2/\text{DOF}$ .

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>Data | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$<br>MC | Relative difference wrt MC |
|------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------|
| track $\chi^2/\text{DOF}$    | 0.00066                                       | 0.00097                                     | -0.32                      |
| $n_{\text{SCT}}$ hits        | 0.00126                                       | 0.00097                                     | 0.29                       |
| $n_{\text{SCT}}$ holes       | 0.00118                                       | 0.00097                                     | 0.21                       |
| $n_{\text{SCT}}$ shared hits | 0.00098                                       | 0.00097                                     | 0.01                       |

The overall uncertainties are around 35% for  $\langle \mu \rangle > 25$ .

**For  $\langle \mu \rangle > 25$  &&  $\langle \mu \rangle < 40$**

Table B.9: Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the LooseWP.

|                                                                | $N_{\text{tracks}}^{\text{data}}$ | $\frac{F_{\text{trk}}}{R_{\text{trk}}} [\%]$ | $\varepsilon$ data [%] | $\varepsilon$ MC [%] |
|----------------------------------------------------------------|-----------------------------------|----------------------------------------------|------------------------|----------------------|
| pre-selection                                                  | 29265106                          | 0.109                                        | -                      | -                    |
| + $ d_0  > 0.2$                                                | 222034                            | 3.655                                        | 0.8                    | 0.7                  |
| + $\sin \theta \times  z_{PV}^0  > 0.3$                        | 14447                             | 7.159                                        | 6.5                    | 6.2                  |
| + track $\chi^2/\text{DOF} \geq 1.2$                           | 6695                              | 15.395                                       | 46.3                   | 45.7                 |
| + $n_{\text{SCT}} < 9$ , + $n_{\text{Pixel}} > 0$              | 4744                              | 19.517                                       | 70.9                   | 70.7                 |
| + $(n_{\text{TRT}} + n_{\text{TRT Outliers}}) < 36$ (final CR) | 3941                              | 21.831                                       | 83.1                   | 83.7                 |

Table B.10: LooseWP. Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the  $\chi^2/\text{DOF}$  of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column.

| Selected variable            | $f_{\text{CR MLE}}^{\text{fakeTrk}}$ | $f_{\text{CR Toys}}^{\text{fakeTrk}}$ | $f_{\text{CR Histo } \chi^2/\text{DOF}}^{\text{fakeTrk}}$ |
|------------------------------|--------------------------------------|---------------------------------------|-----------------------------------------------------------|
| track $\chi^2/\text{DOF}$    | $0.15482 \pm 0.02802$                | $0.18362 \pm 0.03052$                 | $0.17282^{+0.03052}_{-0.03032}$                           |
| $n_{\text{SCT}}$ hits        | $0.20442 \pm 0.03212$                | $0.19472 \pm 0.03092$                 | $0.19342^{+0.06502}_{-0.06642}$                           |
| $n_{\text{SCT}}$ holes       | $0.18982 \pm 0.03132$                | $0.18472 \pm 0.03012$                 | $0.18572^{+0.03112}_{-0.03082}$                           |
| $n_{\text{SCT}}$ shared hits | $0.15782 \pm 0.03272$                | $0.13272 \pm 0.04632$                 | $0.12992^{+0.03012}_{-0.02992}$                           |

Table B.11: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the fit of the selected distributions.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00102                               | 0.00109                               | -0.07                      |
| $n_{\text{SCT}}$ hits        | 0.00134                               | 0.00109                               | 0.23                       |
| $n_{\text{SCT}}$ holes       | 0.00125                               | 0.00109                               | 0.14                       |
| $n_{\text{SCT}}$ shared hits | 0.00104                               | 0.00109                               | -0.05                      |

Table B.12: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the toys experiment.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00114                               | 0.00109                               | 0.04                       |
| $n_{\text{SCT}}$ hits        | 0.00128                               | 0.00109                               | 0.17                       |
| $n_{\text{SCT}}$ holes       | 0.00121                               | 0.00109                               | 0.11                       |
| $n_{\text{SCT}}$ shared hits | 0.00087                               | 0.00109                               | -0.20                      |

Table B.13: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the histogram  $\chi^2/\text{DOF}$ .

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00113                               | 0.00109                               | 0.04                       |
| $n_{\text{SCT}}$ hits        | 0.00127                               | 0.00109                               | 0.16                       |
| $n_{\text{SCT}}$ holes       | 0.00122                               | 0.00109                               | 0.12                       |
| $n_{\text{SCT}}$ shared hits | 0.00085                               | 0.00109                               | -0.22                      |

The overall uncertainties are around 30% for  $\langle \mu \rangle > 25$  &&  $\langle \mu \rangle < 40$ .

**For  $\langle \mu \rangle > 40$**

Table B.14: Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the LooseWP.

|                                                                | $N_{\text{tracks}}^{\text{data}}$ | $\frac{F_{\text{trk}}}{R_{\text{trk}}} [\%]$ | $\varepsilon$ data [%] | $\varepsilon$ MC [%] |
|----------------------------------------------------------------|-----------------------------------|----------------------------------------------|------------------------|----------------------|
| pre-selection                                                  | 18292413                          | 0.122                                        | -                      | -                    |
| + $ d_0  > 0.2$                                                | 138538                            | 4.225                                        | 0.8                    | 0.7                  |
| + $\sin \theta \times  z_{PV}^0  > 0.3$                        | 8682                              | 8.162                                        | 6.3                    | 5.9                  |
| + track $\chi^2/\text{DOF} \geq 1.2$                           | 3909                              | 17.501                                       | 45                     | 46.4                 |
| + $n_{\text{SCT}} < 9$ , + $n_{\text{Pixel}} > 0$              | 2808                              | 22.090                                       | 71.8                   | 73.2                 |
| + $(n_{\text{TRT}} + n_{\text{TRT Outliers}}) < 36$ (final CR) | 2253                              | 24.571                                       | 80.2                   | 78.7                 |

Table B.15: LooseWP. Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the  $\chi^2/\text{DOF}$  of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column.

| Selected variable            | $f_{\text{CR MLE}}^{\text{fakeTrk}}$ | $f_{\text{CR Toys}}^{\text{fakeTrk}}$ | $f_{\text{CR Histo } \chi^2/\text{DOF}}^{\text{fakeTrk}}$ |
|------------------------------|--------------------------------------|---------------------------------------|-----------------------------------------------------------|
| track $\chi^2/\text{DOF}$    | $0.20202 \pm 0.02802$                | $0.19802 \pm 0.03052$                 | $0.19032^{+0.03052}_{-0.03032}$                           |
| $n_{\text{SCT}}$ hits        | $0.25412 \pm 0.03212$                | $0.24862 \pm 0.03092$                 | $0.21362^{+0.06502}_{-0.06642}$                           |
| $n_{\text{SCT}}$ holes       | $0.20562 \pm 0.03132$                | $0.21782 \pm 0.03012$                 | $0.24992^{+0.03112}_{-0.03082}$                           |
| $n_{\text{SCT}}$ shared hits | $0.14832 \pm 0.03272$                | $0.13522 \pm 0.04632$                 | $0.21712^{+0.03012}_{-0.02992}$                           |

Table B.16: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the fit of the selected distributions.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00131                               | 0.00122                               | 0.08                       |
| $n_{\text{SCT}}$ hits        | 0.00165                               | 0.00122                               | 0.36                       |
| $n_{\text{SCT}}$ holes       | 0.00134                               | 0.00122                               | 0.10                       |
| $n_{\text{SCT}}$ shared hits | 0.00096                               | 0.00122                               | -0.21                      |

Table B.17: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the toys experiment.

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00129                               | 0.00122                               | 0.06                       |
| $n_{\text{SCT}}$ hits        | 0.00162                               | 0.00122                               | 0.33                       |
| $n_{\text{SCT}}$ holes       | 0.00142                               | 0.00122                               | 0.16                       |
| $n_{\text{SCT}}$ shared hits | 0.00088                               | 0.00122                               | -0.28                      |

Table B.18: LooseWP. Fraction of fake tracks at pre-selection level,  $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ .  $f_{\text{CR}}^{\text{fakeTrk}}$  is taken from the histogram  $\chi^2/\text{DOF}$ .

| Selected variable            | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ | Relative difference wrt MC |
|------------------------------|---------------------------------------|---------------------------------------|----------------------------|
|                              | Data                                  | MC                                    |                            |
| track $\chi^2/\text{DOF}$    | 0.00124                               | 0.00122                               | 0.02                       |
| $n_{\text{SCT}}$ hits        | 0.00149                               | 0.00122                               | 0.14                       |
| $n_{\text{SCT}}$ holes       | 0.00162                               | 0.00122                               | 0.33                       |
| $n_{\text{SCT}}$ shared hits | 0.00141                               | 0.00122                               | 0.16                       |

The overall uncertainties are less than 36% for  $\langle \mu \rangle > 40$ .

# Appendix C

## Additional data for pMSSM

### Interpretation studies

This appendix supplements Chapter 7 by presenting the distributions of 19 **pMSSM** parameters and constraints of the 19D **pMSSM** model parameters. In constraints, the variables include the flavour physics branching ratios, electroweak precision observables, and dark matter direct detection experiments, as outlined in Table 7.2.

### 19D pMSSM parameters distributions and exclusion fraction

---

The one-dimensional distributions in this appendix are as follows:

- (a) Displaying the distribution of all models before and after applying ATLAS experiment constraints, where the blue dashed line indicates constraints related only to ATLAS Higgs studies;
- (b) Showing the distribution of all models after applying non-ATLAS experiment constraints, after applying both non-ATLAS experiment constraints and ATLAS Higgs study constraints, and after applying both non-ATLAS experiment constraints and ATLAS experiment constraints.

The two-dimensional distributions in this appendix are as follows:

- (a) Considering all models;
- (b) Considering models constrained by non-ATLAS experiments;
- (c) Considering models constrained by both non-ATLAS experiments and ATLAS Higgs study constraints.



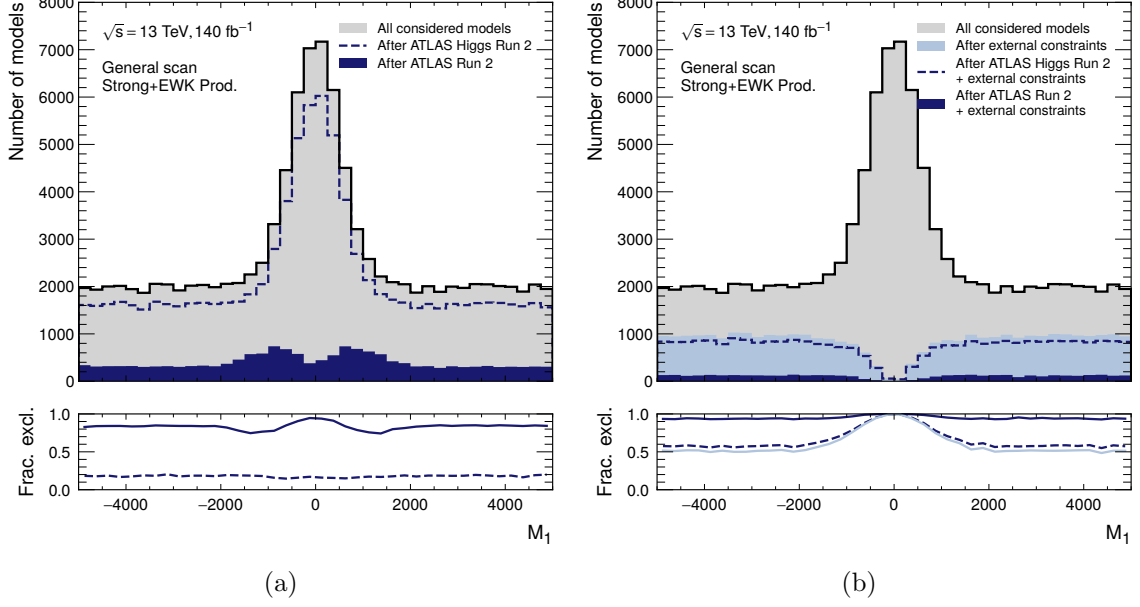


Figure C.1: Analysis of  $M_1$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

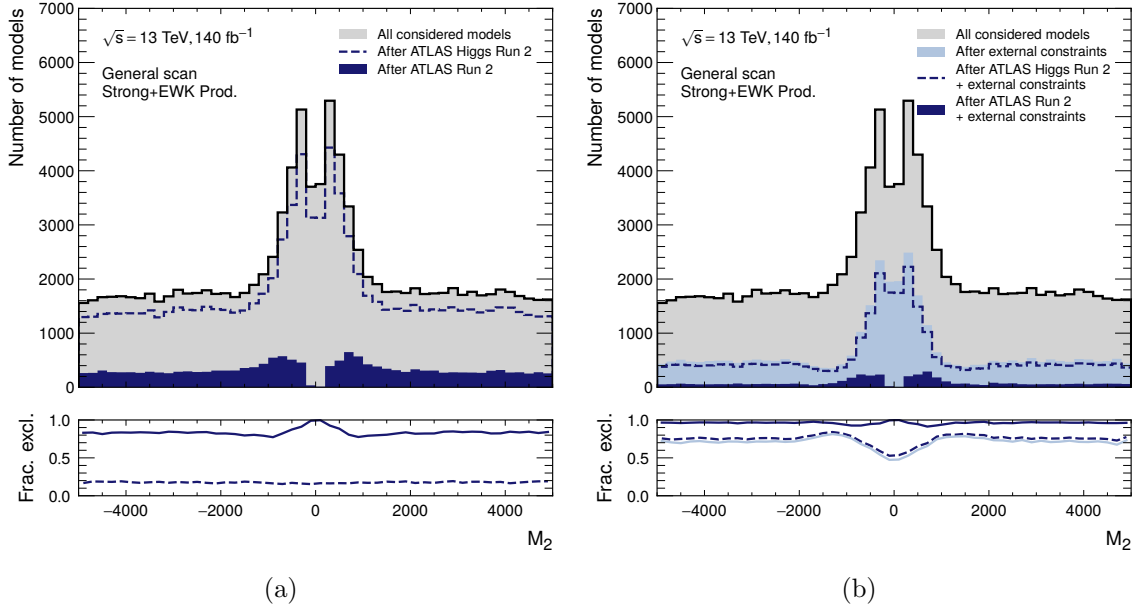


Figure C.2: Analysis of  $M_2$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

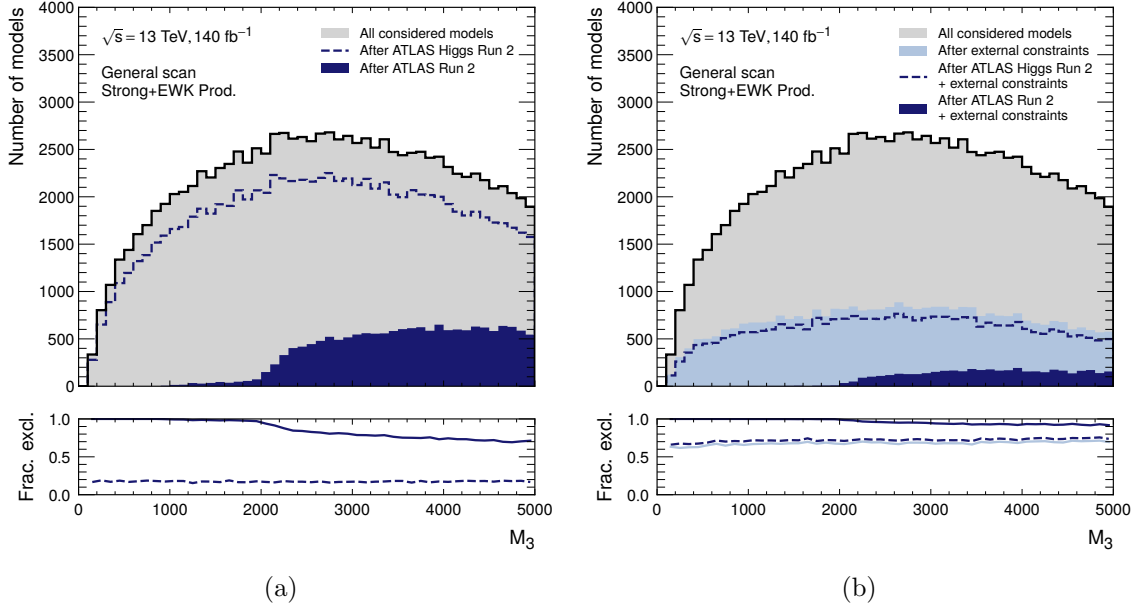


Figure C.3: Analysis of  $M_3$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

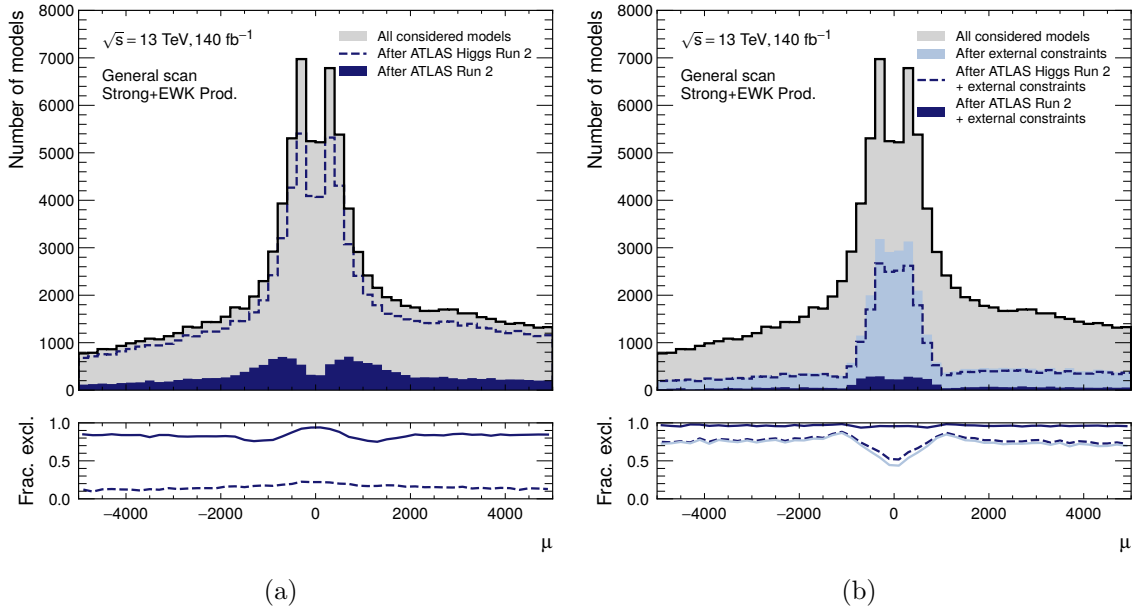


Figure C.4: Analysis of  $\mu$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

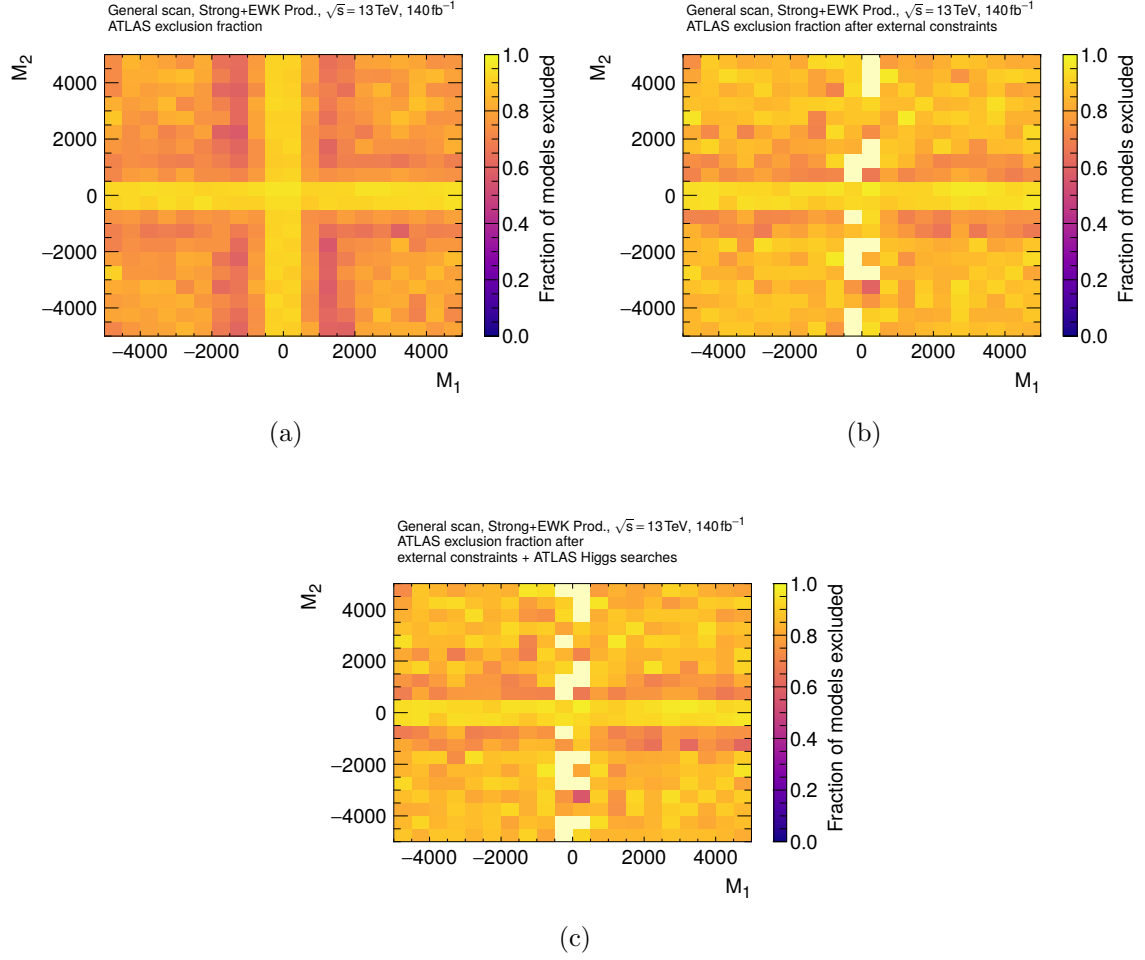


Figure C.5: Proportion of General Scan Models Eliminated by ATLAS Run 2 SUSY Outcomes with Strong and EWK Production Illustrated on the  $M_1$  vs.  $M_2$  Plane. Figure (a) encompasses all models, (b) encompasses models that withstand all external constraints, (c) encompasses models that withstand both the external constraints and the ATLAS Higgs searches.

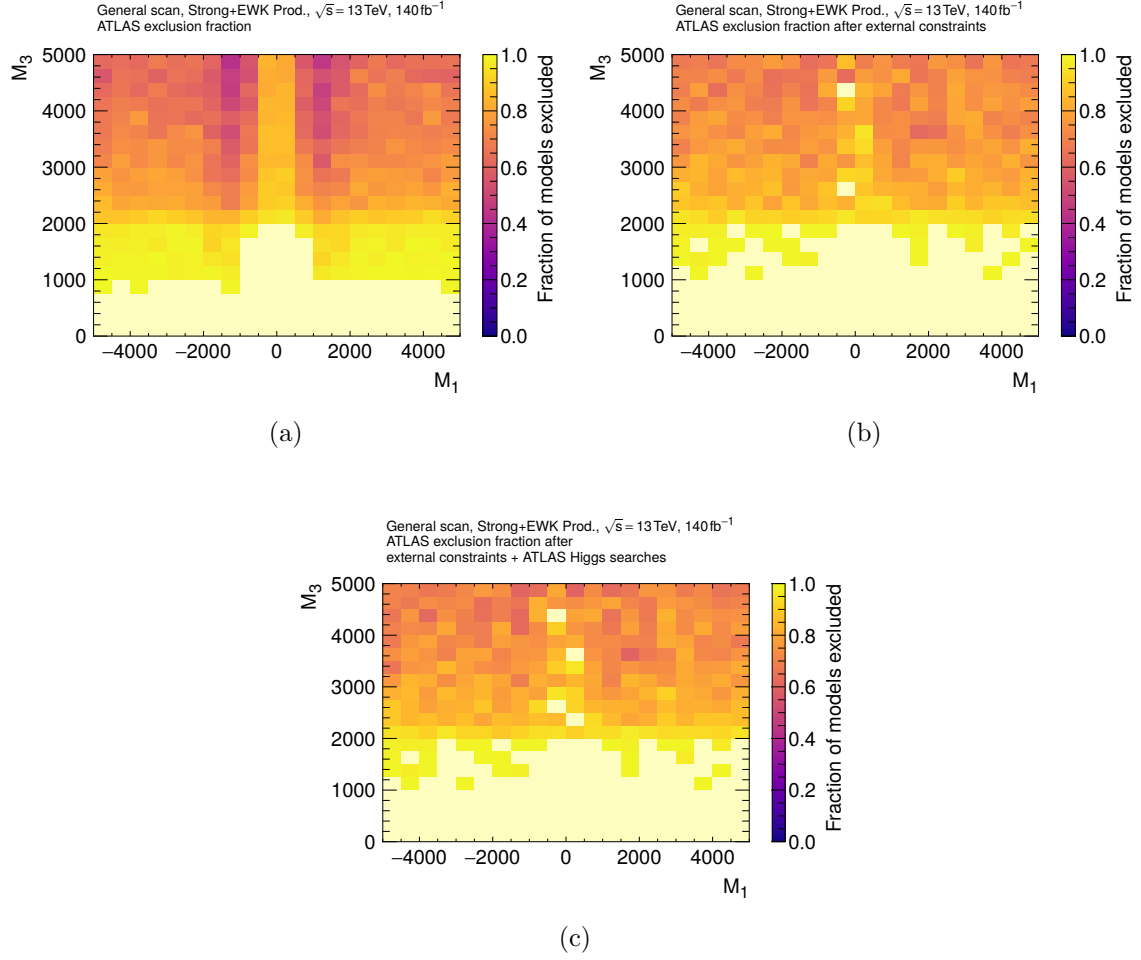


Figure C.6: Proportion of General Scan Models Eliminated by ATLAS Run 2 SUSY Outcomes with Strong and EWK Production Illustrated on the  $M_1$  vs.  $M_3$  Plane. Figure (a) encompasses all models, (b) encompasses models that withstand all external constraints, (c) encompasses models that withstand both the external constraints and the ATLAS Higgs searches.

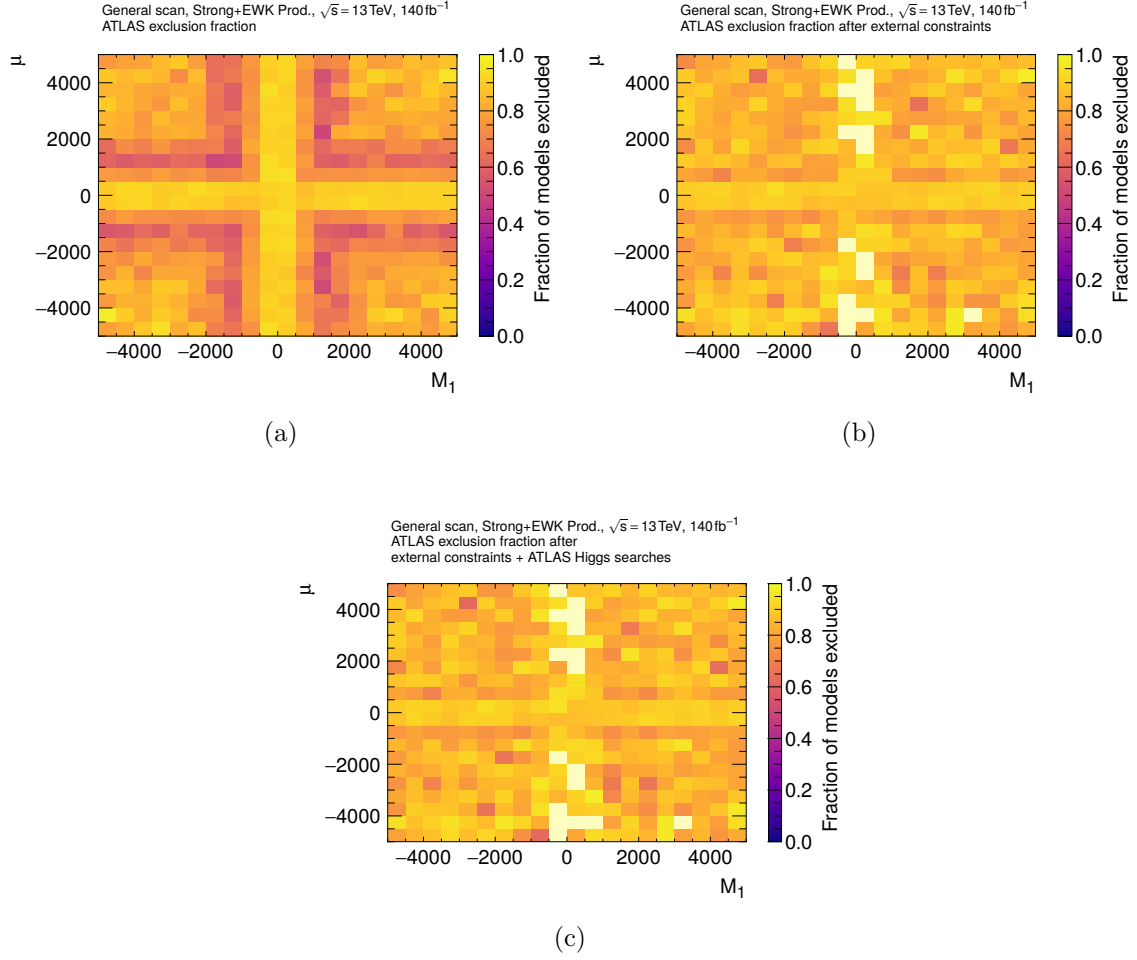


Figure C.7: Proportion of General Scan Models Eliminated by ATLAS Run 2 SUSY Outcomes with Strong and EWK Production Illustrated on the  $M_1$  vs.  $\mu$  Plane. Figure (a) encompasses all models, (b) encompasses models that withstand all external constraints, (c) encompasses models that withstand both the external constraints and the ATLAS Higgs searches.

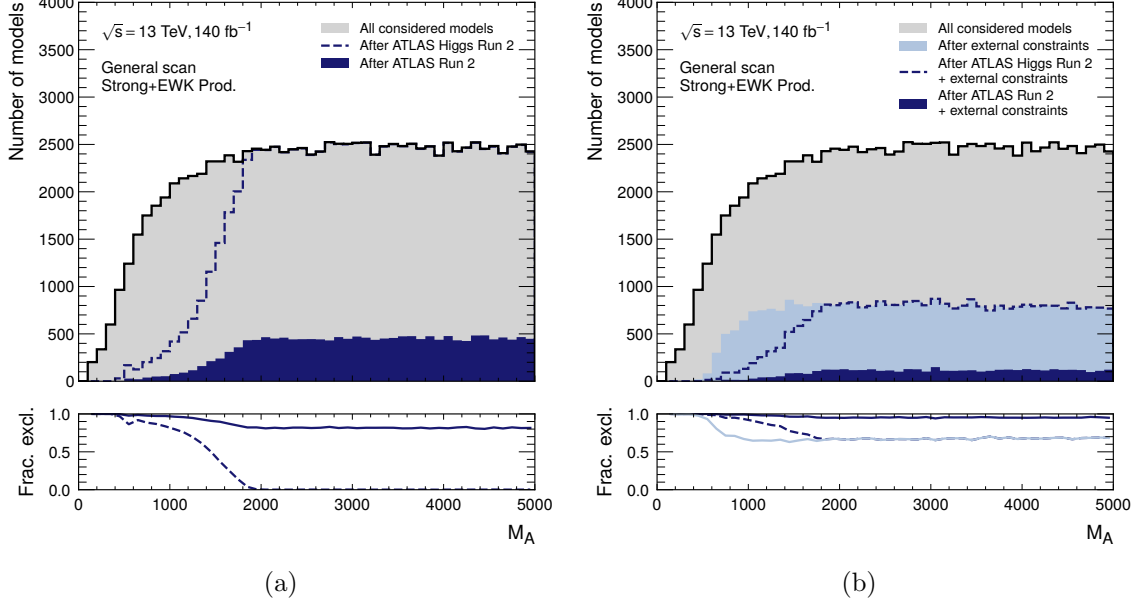


Figure C.8: Analysis of  $M_A$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

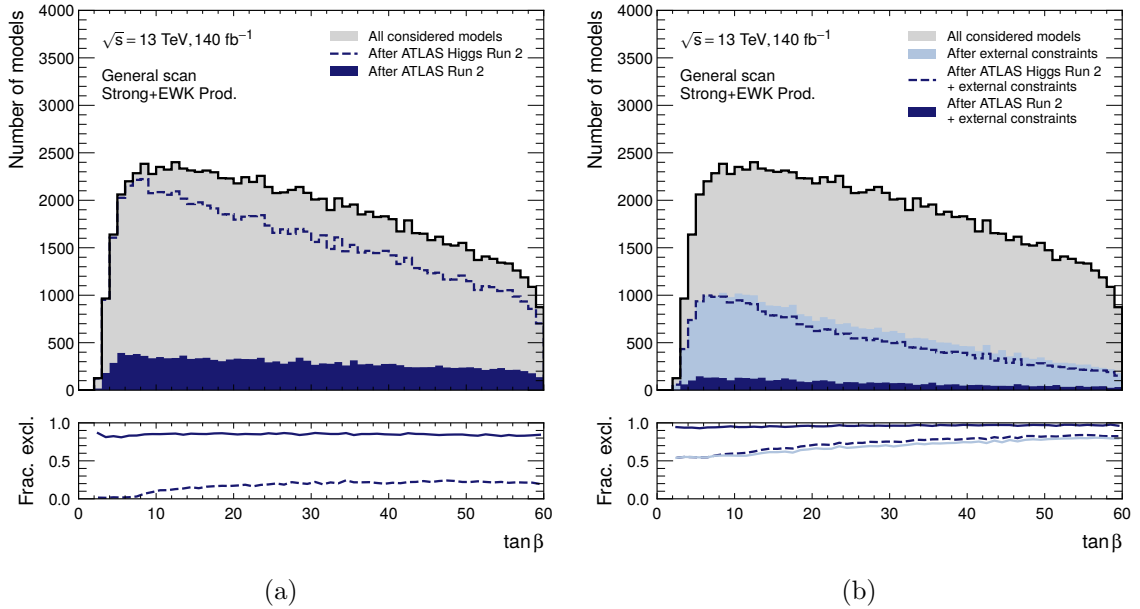


Figure C.9: Analysis of  $\tan\beta$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

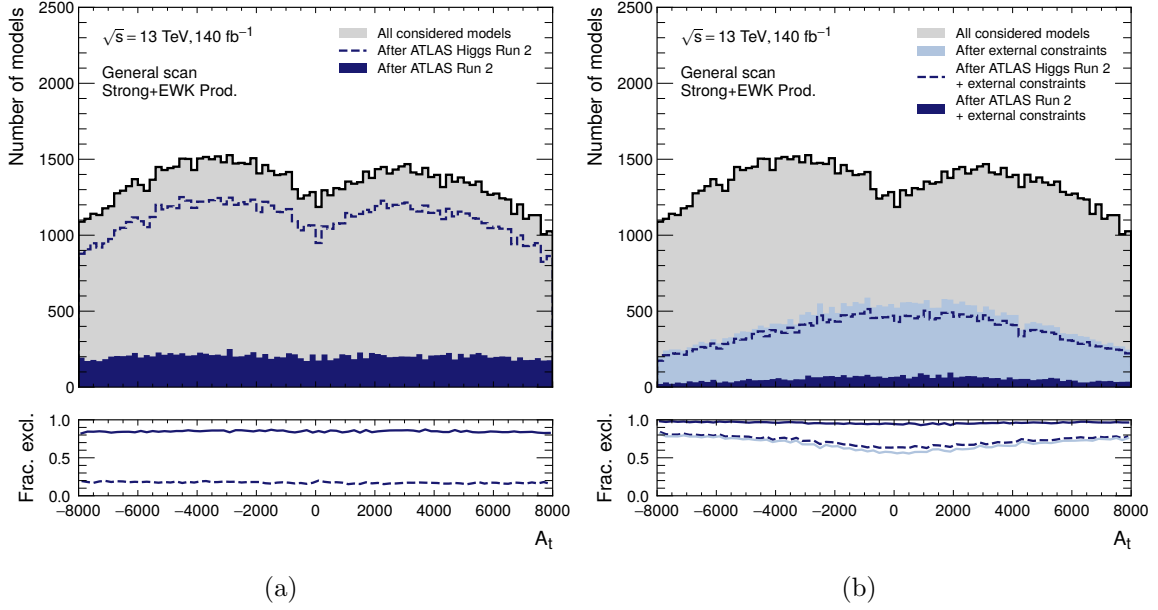


Figure C.10: Analysis of  $A_t$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

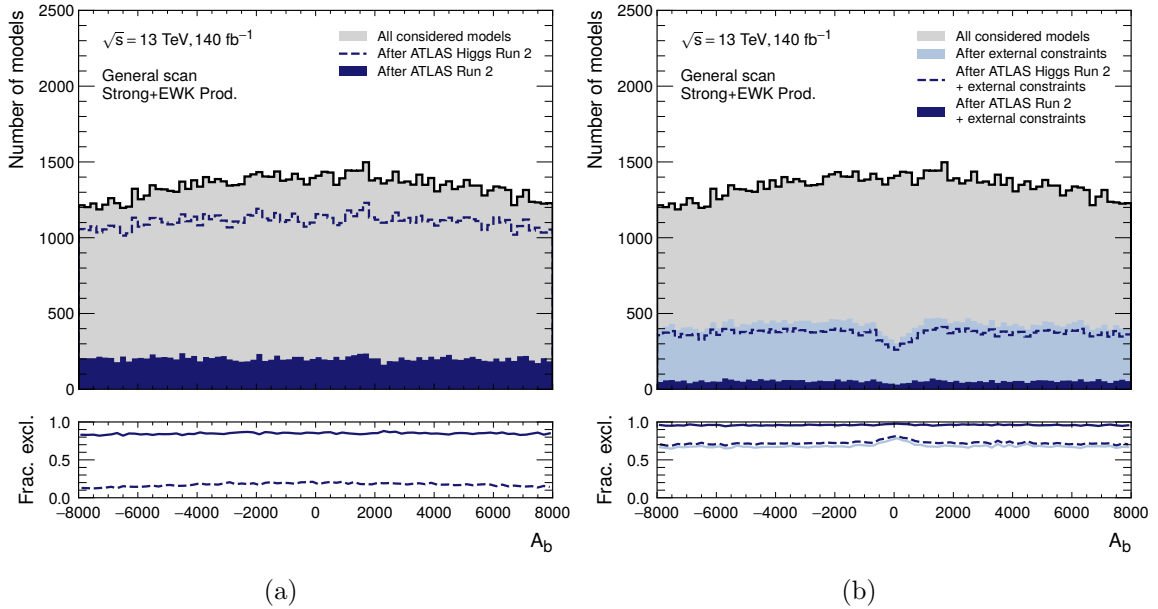


Figure C.11: Analysis of  $A_b$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.

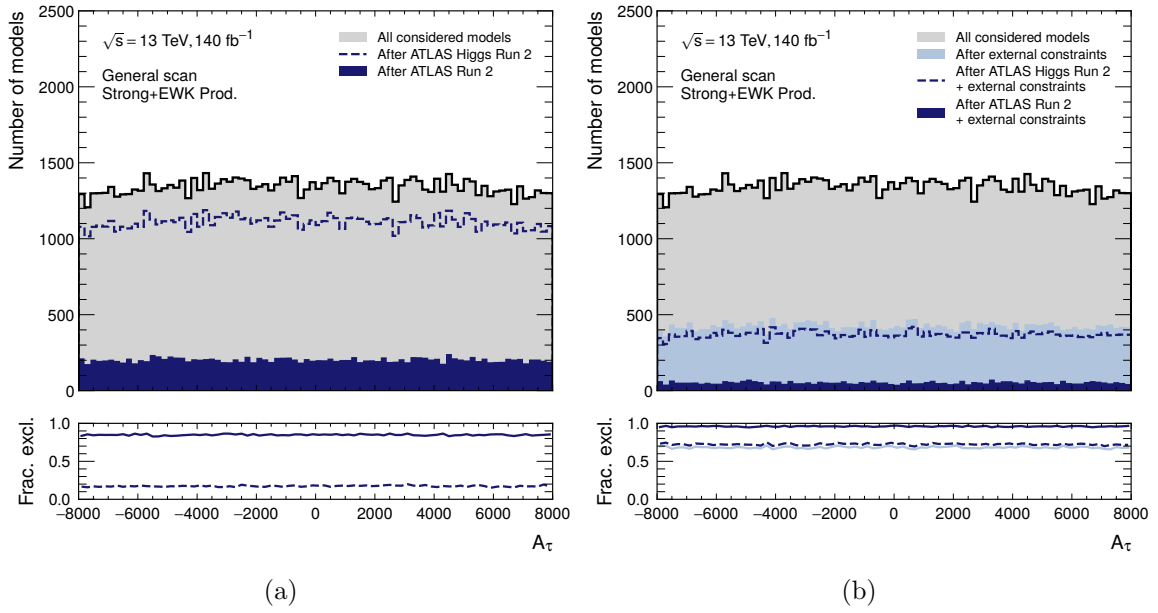


Figure C.12: Analysis of  $A_\tau$  Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario.



# Constraints on the 19D pMSSM Model by Non-ATLAS SUSY Experiments

---

The one-dimensional distributions in this section are as follows:

- The left column of images displays the electroweak production processes of the **pMSSM** model;
- The right column of images displays the strong interaction production processes of the **pMSSM** model;
- All images show the distributions of the relevant models after applying ATLAS Higgs study constraints and after applying ATLAS experiment constraints.

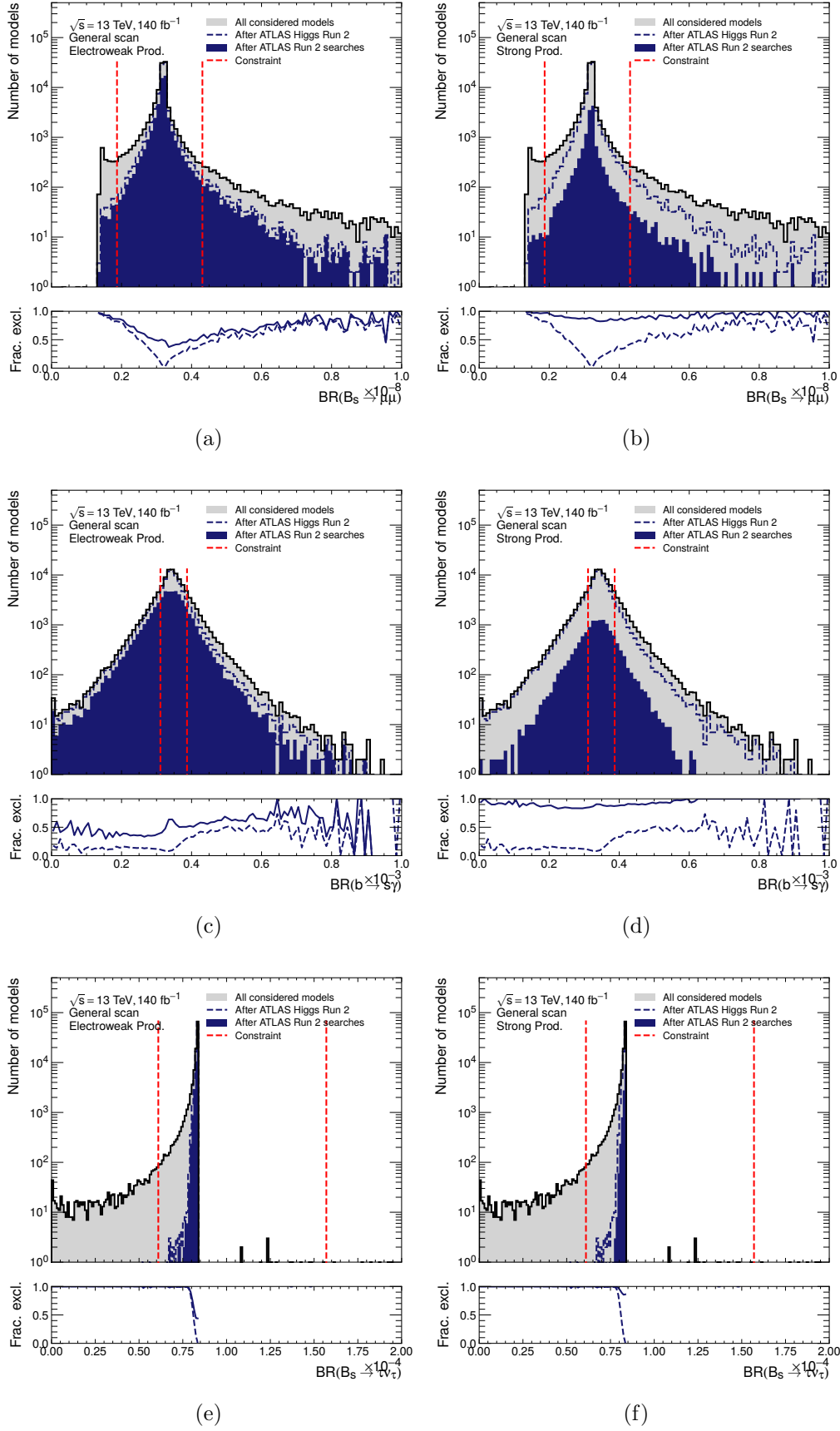


Figure C.13: Variable Distributions of Flavour Physics Constraints Prior to and Following the Enforcement of ATLAS Run 2 Constraints. The blue dashed line indicates the models that remain after the application of the ATLAS Higgs constraints. In the display, the first column depicts the distribution for EWK production, while the second column presents the distribution for Strong production.

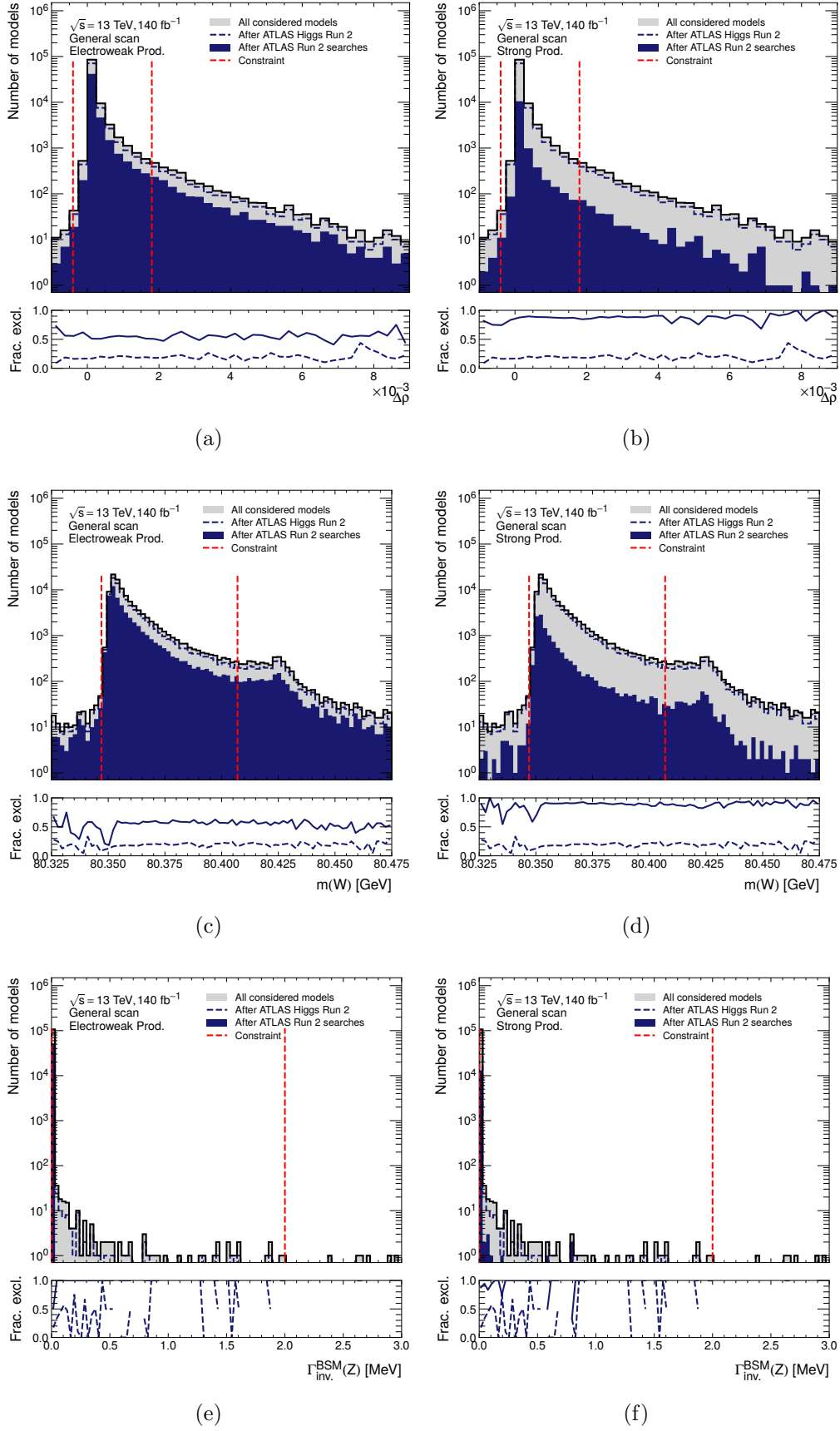


Figure C.14: Variable Distributions of Precision electroweak observables Constraints Prior to and Following the Enforcement of ATLAS Run 2 Constraints. The blue dashed line indicates the models that remain after the application of the ATLAS Higgs constraints. In the display, the first column depicts the distribution for EWK production, while the second column presents the distribution for Strong production.

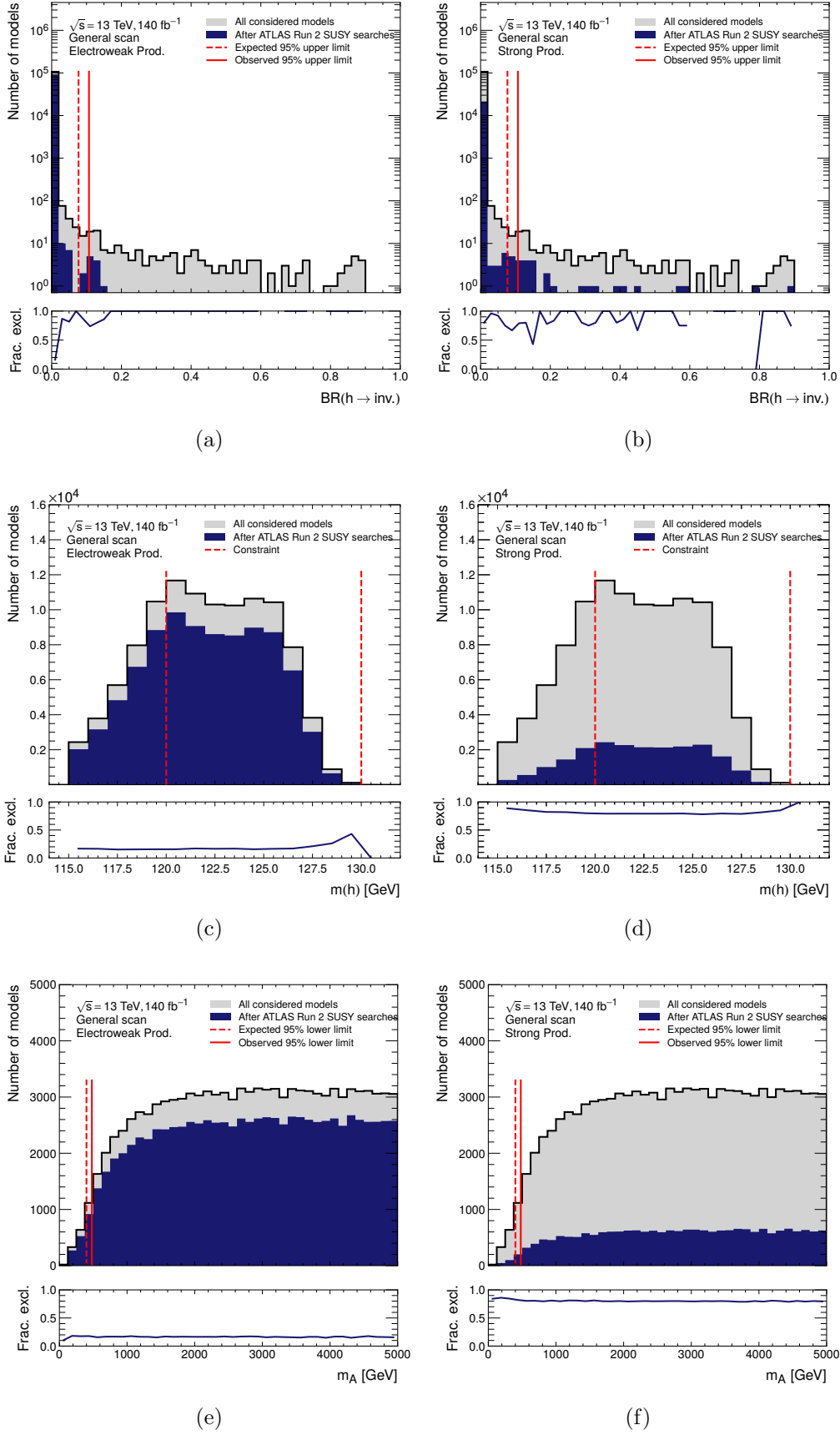


Figure C.15: Distributions of Variables Subject to ATLAS Higgs Constraints Before and After Implementing ATLAS Run 2 Constraints. The blue dashed line delineates the models that continue after the ATLAS Higgs constraints. The distribution of EWK production is represented in the first column, and that of Strong production in the second column.

# Acronyms

**SM** Standard Model

**LHC** Large Hadron Collider

**LHCb** Large Hadron Collider beauty

**ATLAS** A Toroidal LHC Apparatus

**CMS** Compact Muon Solenoid

**BSM** Beyond Standard Model

**MLE** Maximum Likelihood Estimation

**SUSY** Supersymmetry

**EM** Electromagnetic

**EW** Electroweak

**GUT** Grand Unification Theory

**LEP** Leptonic

**QCD** Quantum Chromodynamics

**QED** Quantum Electrodynamics

**DM** Dark Matter

**mSUGRA** Minimal Supergravity

**AMSB** Anomaly-Mediated Supersymmetry Breaking

**GMSB** Gauge-Mediated Supersymmetry Breaking

**WIMPs** Weakly Interacting Massive Particles

**pMSSM** phenomenological Minimal Supersymmetry Standard Model

**MSSM** Minimal Supersymmetry Standard Model

**LSP** Lightest Supersymmetric Particle

**WIMP** Weakly Interacting Massive Particles

**MET** Missing Transverse Energy

**PSB** Proton Synchrotron Booster

**PS** Proton Synchrotron

**SPS** Super Proton Synchrotron  
**EWkino** Electroweakino  
**HL-LHC** High-Luminosity Large Hadron Collider  
**HLT** High-level trigger  
**GSF** Gaussian-Sum Filter  
**JVT** Jet Vertex Tagger  
**LCW** Local cluster weighting  
**cMSSM** Constrained Minimal Supersymmetric Standard Model  
**PDG** Particle Data Group  
**QGP** Quark Gluon Plasma  
**P-flow** particle flow  
**FT** Fake Tracks  
**SRs** Signal Regions  
**CR** Control Region  
**CERN** The European Organization for Nuclear Research  
**SCT** Semiconductor Tracker  
**TRT** Transition Radiation Tracker  
**IBL** Insertable B-Layer  
**ECAL** Electromagnetic Calorimeter  
**HCAL** Hadronic Calorimeter  
**ID** Inner Detector  
**LAr** Liquid Argon  
**TGCs** Thin gap chambers  
**CSCs** Cathode strip chambers  
**RPCs** Resistive plate chambers  
**MDTs** Monitored drift tubes  
**MC** Monte Carlo Simulations  
**MS** Muon Spectrometer  
**ME** Muon-spectrometer Extrapolated  
**IO** Inside-out  
**CB** Combined  
**ST** Segment-tagged  
**LZ** LUX-ZEPLIN  
**CT** Calorimeter-tagged

**CL** Confidence level

**rel21** ATLAS rel21: Release 21 of the ATLAS computing release

**rel22** ATLAS rel22: Release 22 of the ATLAS computing release

# Bibliography

- [1] F. Hanzel and A. D. Martin, “Quarks and leptons: An introductory course in modern particle physics,” 1984.
- [2] W. N. Cottingham and D. A. Greenwood, *An introduction to the standard model of particle physics*. Cambridge University Press, 2007.
- [3] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*. CRC Press, 1st ed., 1995.
- [4] S. P. Martin, “A supersymmetry primer,” in *Perspectives on supersymmetry II*, pp. 1–153, World Scientific, 2010. [http://dx.doi.org/10.1142/9789812839657\\_0001](http://dx.doi.org/10.1142/9789812839657_0001).
- [5] I. J. R. Aitchison, “Supersymmetry and the mssm: An elementary introduction,” 2005. <https://arxiv.org/abs/hep-ph/0505105>.
- [6] J. Thomson, “On the structure of the atom: an investigation of the stability and periods of oscillation of a number of corpuscles arranged at equal intervals around the circumference of a circle; with application of the results to the theory of atomic structure,” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 7, no. 39, pp. 237–265, 1904. <https://doi.org/10.1080/14786440409463107>.
- [7] E. Rutherford, “Lxxix. the scattering of  $\alpha$  and  $\beta$  particles by matter and the structure of the atom,” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 21, no. 125, pp. 669–688, 1911. <https://doi.org/10.1080/14786440508637080>.
- [8] H. Kragh, *Niels Bohr and the quantum atom: The Bohr model of atomic structure 1913-1925*. OUP Oxford, 2012. <https://doi.org/10.1093/acprof:oso/9780199654987.001.0001>.



- [9] P. D. Group, R. Workman, V. Burkert, V. Crede, E. Klempt, U. Thoma, L. Tiator, K. Agashe, G. Aielli, B. Allanach, *et al.*, “Review of particle physics,” *Progress of theoretical and experimental physics*, vol. 2022, no. 8, p. 083C01, 2022. <https://doi.org/10.1093/ptep/ptac097>.
- [10] E. Noether, “Invariant variation problems,” *Transport Theory and Statistical Physics*, vol. 1, p. 186–207, 1971. <http://dx.doi.org/10.1080/00411457108231446>.
- [11] S. L. Glashow, “Partial-symmetries of weak interactions,” *Nuclear Physics*, vol. 22, pp. 579–588, 1961. <https://www.sciencedirect.com/science/article/pii/0029558261904692>.
- [12] N. Dombey, “Abdus salam: A reappraisal. part i. how to win the nobel prize,” *arXiv preprint arXiv:1109.1972*, 2011. <https://arxiv.org/abs/1109.1972>.
- [13] S. Weinberg, “A model of leptons,” *Physical review letters*, vol. 19, p. 1264, 1967. <https://link.aps.org/doi/10.1103/PhysRevLett.19.1264>.
- [14] P. W. Anderson, “Plasmons, gauge invariance, and mass,” *Physical Review*, vol. 130, no. 1, p. 439, 1963. <https://link.aps.org/doi/10.1103/PhysRev.130.439>.
- [15] P. W. Higgs, “Broken symmetries and the masses of gauge bosons,” *Physical review letters*, vol. 13, no. 16, p. 508, 1964. <https://link.aps.org/doi/10.1103/PhysRevLett.13.508>.
- [16] F. Englert and R. Brout, “Broken symmetry and the mass of gauge vector mesons,” *Physical review letters*, vol. 13, no. 9, p. 321, 1964. <https://link.aps.org/doi/10.1103/PhysRevLett.13.321>.
- [17] Super-Kamiokande Collaboration, “Evidence for oscillation of atmospheric neutrinos,” *Physical review letters*, vol. 81, no. 8, pp. 1562–1567, 1998. <https://link.aps.org/doi/10.1103/PhysRevLett.81.1562>.
- [18] SNO Collaboration, “Direct evidence for neutrino flavor transformation from neutral-current interactions in the sudbury neutrino observatory,” *Physical review letters*, vol. 89, no. 1, p. 011301, 2002. <https://link.aps.org/doi/10.1103/PhysRevLett.89.011301>.
- [19] H. Belich, T. Costa-Soares, M. Ferreira Jr, J. Helayël-Neto, and M. Orlando, “A comment on the topological phase for anti-particles in a lorentz-violating environment,” *Physics*

- Letters B*, vol. 639, no. 6, pp. 675–678, 2006. <http://dx.doi.org/10.1016/j.physletb.2006.07.003>.
- [20] S. Raby, “Grand unified theories,” 2006. <https://arxiv.org/abs/hep-ph/0608183>.
- [21] P. D. Group”, P. Zyla, R. Barnett, J. Beringer, O. Dahl, D. Dwyer, D. Groom, C.-J. Lin, K. Lugovsky, E. Pianori, *et al.*, “Review of particle physics,” *Progress of Theoretical and Experimental Physics*, vol. 2020, no. 8, p. 083C01, 2020. <https://doi.org/10.1093/ptep/ptac097>.
- [22] V. C. Rubin, W. K. Ford Jr, and N. Thonnard, “Rotational properties of 21 sc galaxies with a large range of luminosities and radii, from ngc 4605/r= 4kpc/to ugc 2885/r= 122 kpc,” *Astrophysical Journal*, vol. 238, pp. 471–487, 1980. <https://ui.adsabs.harvard.edu/abs/1980ApJ...238..471R>.
- [23] E. Corbelli and P. Salucci, “The extended rotation curve and the dark matter halo of m33,” *Monthly Notices of the Royal Astronomical Society*, vol. 311, no. 2, pp. 441–447, 2000. <https://doi.org/10.48550/arXiv.astro-ph/9909252>.
- [24] J. A. Tyson, G. P. Kochanski, and I. P. Dell’Antonio, “Detailed mass map of cl 0024+1654 from strong lensing,” *Astrophysical Journal*, vol. 498, no. 2, p. L107, 1998. <http://dx.doi.org/10.1086/311314>.
- [25] A. D. Lewis, D. A. Buote, and J. T. Stocke, “Chandra observations of a2029: The dark matter profile down to below 0.01 r<sub>vir</sub> in an unusually relaxed cluster,” *Astrophysical Journal*, vol. 586, no. 1, p. 135, 2003. <http://dx.doi.org/10.1086/367556>.
- [26] S. W. Allen, A. E. Evrard, and A. B. Mantz, “Cosmological parameters from observations of galaxy clusters,” *Annual Review of Astronomy and Astrophysics*, vol. 49, pp. 409–470, 2011. <http://dx.doi.org/10.1146/annurev-astro-081710-102514>.
- [27] A. Liddle, *An introduction to modern cosmology*. John Wiley & Sons, 2015.
- [28] S. Dimopoulos, S. Raby, and F. Wilczek, “Supersymmetry and the scale of unification,” *Physical Review D*, vol. 24, no. 6, p. 1681, 1981. <https://link.aps.org/doi/10.1103/PhysRevD.24.1681>.
- [29] L. E. Ibanez and G. G. Ross, “Low-energy predictions in supersymmetric grand unified theories,” *Physics Letters B*, vol. 105, no. 6, pp. 439–442, 1981. [https://doi.org/10.1016/0370-2693\(81\)91200-4](https://doi.org/10.1016/0370-2693(81)91200-4).

- [30] J. Wess and B. Zumino, “Supergauge transformations in four dimensions,” *Nuclear Physics B*, vol. 70, no. 1, pp. 39–50, 1974. [https://doi.org/10.1016/0550-3213\(74\)90355-1](https://doi.org/10.1016/0550-3213(74)90355-1).
- [31] A. Salam and J. Strathdee, “Super-symmetry and non-abelian gauges,” *Physics Letters B*, vol. 51, pp. 353–355, 1974. [https://doi.org/10.1016/0370-2693\(74\)90226-3](https://doi.org/10.1016/0370-2693(74)90226-3).
- [32] Y. A. Gol’fand and E. P. Likhtman, *Extension of the algebra of Poincaré group generators and violation of P invariance*. 1989. [https://www.worldscientific.com/doi/abs/10.1142/9789814542340\\_0001](https://www.worldscientific.com/doi/abs/10.1142/9789814542340_0001).
- [33] D. Volkov and V. Akulov, “Is the neutrino a goldstone particle?,” *Physics Letters B*, vol. 46, no. 1, pp. 109–110, 1973. [https://doi.org/10.1016/0370-2693\(73\)90490-5](https://doi.org/10.1016/0370-2693(73)90490-5).
- [34] S. Ferrara and B. Zumino, “Supergauge invariant yang-mills theories,” *Nuclear Physics B*, vol. 79, no. 3, pp. 413–421, 1974. [https://doi.org/10.1016/0550-3213\(74\)90559-8](https://doi.org/10.1016/0550-3213(74)90559-8).
- [35] N. Sakai, “Naturalnes in supersymmetric guts,” *Zeitschrift für Physik C Particles and Fields*, vol. 11, pp. 153–157, 1981. <https://doi.org/10.1007/BF01573998>.
- [36] G. R. Farrar and P. Fayet, “Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry,” *Physics Letters B*, vol. 76, pp. 575–579, 1978. [https://doi.org/10.1016/0370-2693\(78\)90858-4](https://doi.org/10.1016/0370-2693(78)90858-4).
- [37] R. N. Mohapatra, “Supersymmetry and R-parity: an Overview,” *Physica Scripta*, vol. 90, no. 8, p. 088004, 2015. <https://doi.org/10.48550/arXiv.1503.06478>.
- [38] J. L. Feng and T. Moroi, “Supernatural supersymmetry: phenomenological implications of anomaly-mediated supersymmetry breaking,” *Physical Review D*, vol. 61, no. 9, p. 095004, 2000. <http://dx.doi.org/10.1103/PhysRevD.61.095004>.
- [39] S. Dimopoulos and H. Georgi, “Softly broken supersymmetry and su (5),” *Nuclear Physics B*, vol. 193, no. 1, pp. 150–162, 1981. [https://doi.org/10.1016/0550-3213\(81\)90522-8](https://doi.org/10.1016/0550-3213(81)90522-8).
- [40] LHC SUSY Cross Sections Working Group, “Susy cross sections at  $\sqrt{s} = 13$  tev.” <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections>.
- [41] A. Cervelli, “Searches for supersymmetry in atlas,” *nternational Journal of Modern Physics: Conference Series*, vol. 47, 2018. <https://doi.org/10.1142/S2010194518600881>.

- [42] ATLAS Collaboration, “Search for new phenomena in final states with large jet multiplicities and missing transverse momentum with atlas using  $\sqrt{s} = 13$  tev proton-proton collisions,” *arXiv preprint arXiv:1602.06194*, 2016. <https://doi.org/10.1016/j.physletb.2016.04.005>.
- [43] ATLAS Collaboration, “Search for direct stau production in events with two hadronic  $\tau$ -leptons in  $\sqrt{s} = 13$  tev pp collisions with atlas detector,” *Physical Review D*, vol. 101, pp. 032009–30, 2020. <https://doi.org/10.1103/PhysRevD.101.032009>.
- [44] ATLAS Collaboration, “Search for squarks and gluinos in final states with one isolated lepton, jets, and missing transverse momentum at  $\sqrt{s} = 13$  tev with atlas detector,” *The European Physical Journal C*, vol. 81, no. 600, p. 600, 2021. <https://doi.org/10.1140/epjc/s10052-021-09344-w>.
- [45] D. Alves *et al.*, “Simplified models for lhc new physics searches,” *Journal of Physics G: Nuclear and Particle Physics*, vol. 39, no. 10, p. 105005, 2012. <https://doi.org/10.48550/arXiv.1105.2838>.
- [46] ATLAS Collaboration, “Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the  $w$ -boson mass in  $\sqrt{s} = 13\text{tev}$  collisions with the atlas detector,” *Journal of High Energy Physics*, vol. 2023, no. 6, pp. 1–59, 2023. <https://doi.org/10.48550/arXiv.2209.13935>.
- [47] R. Cotta, K. Howe, J. Hewett, and T. Rizzo, “Phenomenological minimal supersymmetric standard model dark matter searches on ice,” *Physical Review D*, vol. 85, no. 3, p. 035017, 2012. <https://doi.org/10.1103/PhysRevD.85.035017>.
- [48] C. Abel *et al.*, “Measurement of the permanent electric dipole moment of the neutron,” *Physical Review Letters*, vol. 124, no. 8, p. 081803, 2020. <https://doi.org/10.48550/arXiv.2001.11966>.
- [49] G. D’Ambrosio, G. Giudice, G. Isidori, and A. Strumia, “Minimal flavour violation: An effective field theory approach,” *Nuclear Physics B*, vol. 645, no. 1-2, pp. 155–187, 2002. <https://doi.org/10.48550/arXiv.hep-ph/0207036>.
- [50] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report*. CERN Yellow Reports: Monographs, Geneva: CERN, 2004. <https://cds.cern.ch/record/782076>.

- [51] ATLAS Collaboration, “The atlas experiment at the cern large hadron collider,” *JInst*, vol. 3, 2008. <https://doi.org/10.1088/1748-0221/3/08/S08003>.
- [52] P. Weber, *ATLAS calorimetry: trigger, simulation and jet calibration*. PhD thesis, Kirchhoff Inst. Phys., 2008. <https://cds.cern.ch/record/2284233>.
- [53] C. Campagnari and M. Franklin, “The discovery of the top quark,” *Reviews of Modern Physics*, vol. 69, no. 1, p. 137, 1997. <https://doi.org/10.1103/RevModPhys.69.137>.
- [54] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration and The LEP Working Group for Higgs Boson Searches), “Search for the standard model higgs boson at lep,” *Physics Letters B*, vol. 565, pp. 61–75, 2003.
- [55] J. Erler, “Mass of the higgs boson in the standard electroweak model,” *Physical Review D—Particles, Fields, Gravitation, and Cosmology*, vol. 81, no. 5, p. 051301, 2010. <https://doi.org/10.1103/PhysRevD.81.051301>.
- [56] A. Del Rosso, “Aerial view of the lhc and the four major experiments,” tech. rep., 2017. <http://cds.cern.ch/record/2253966>.
- [57] G. Apollinari, L. Rossi, and O. Brüning, “High luminosity lhc project description,” tech. rep., 2014. <https://cds.cern.ch/record/1974419/files/>.
- [58] E. Lopienska, “The cern accelerator complex, layout in 2022. complexe des accélérateurs du cern en janvier 2022,” *General Photo*, 2022. <https://cds.cern.ch/record/2800984>.
- [59] CMS Collaboration, “The CMS experiment at the CERN LHC,” *JInst*, vol. 3, 2008. <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [60] Alice Collaboration, “The ALICE detector at LHC,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 344, no. 1, pp. 27–38, 1994. [https://doi.org/10.1016/0168-9002\(94\)90647-5](https://doi.org/10.1016/0168-9002(94)90647-5).
- [61] LHCb Collaboration, “The LHCb detector at the LHC,” *Journal of instrumentation*, vol. 3, no. 08, 2008. <https://dx.doi.org/10.1088/1748-0221/3/08/S08005>.
- [62] Atlas Collaboration, “The atlas experiment at the cern large hadron collider: a description of the detector configuration for run 3,” *Journal of Instrumentation*, vol. 19, p. P05063, 5 2024. <http://dx.doi.org/10.1088/1748-0221/19/05/P05063>.

- [63] ATLAS Collaboration, “Luminosity public results run 2,” 2015-2018. <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>.
- [64] ATLAS Collaboration, “Luminosity public results run 2,” 2022-2024. <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3>.
- [65] J. Pequena, “Computer generated image of the whole atlas detector,” 2008. <https://cds.cern.ch/record/109592>.
- [66] P. Schwemling, “Atlas electromagnetic calorimetry and performance of electron/photon detection,” *The European Physical Journal C-Particles and Fields*, vol. 34, pp. s129–s137, 2004. <https://doi.org/10.1140/epjcd/s2004-04-014-x>.
- [67] M. Aleksa *et al.*, “Discussion on the electromagnetic calorimeters of atlas and cms,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 732, pp. 442–450, 2013. <https://doi.org/10.1016/j.nima.2013.05.195>.
- [68] J. Alison, “Measurements of standard model processes at atlas,” *arXiv*, pp. 53–58, 6 2011. <https://doi.org/10.48550/arXiv.1106.1669>.
- [69] “ATLAS EXPERIMENT - PUBLIC RESULTS.” <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>.
- [70] Atlas Collaboration, “Measurements of  $w$  and  $z$  boson production in  $pp$  collisions at  $\sqrt{s}= 5.02$  tev with the atlas detector,” *The European Physical Journal C*, no. 2, 2019. <http://dx.doi.org/10.1140/epjc/s10052-019-6622-x>.
- [71] ATLAS Collaboration, “Measurement of the w-boson mass and width with the atlas detector using proton-proton collisions at  $\sqrt{s}= 7$  tev,” *arXiv*, 2024. <https://doi.org/10.48550/arXiv.2403.15085>.
- [72] D. Melini, “Measurements of the top-quark mass using the atlas detector at the lh,” 11 2022. <https://cds.cern.ch/record/2841614/files/ATL-PHYS-PROC-2022-116.pdf>.
- [73] ATLAS Collaboration, “Performance and calibration of quark/gluon-jet taggers using 140  $fb^{-1}$  of  $pp$  collisions at  $\sqrt{s}= 13$  tev with the atlas detector,” *Chinese Physics C*, vol. 48, p. 023001, 2 2024. <http://dx.doi.org/10.1088/1674-1137/acf701>.

- [74] ATLAS Collaboration, “Observation of a new particle in the search for the standard model higgs boson with the atlas detector at the lhc,” *Physics Letters B*, vol. 716, p. 1–29, 9 2012. <https://doi.org/10.1016/j.physletb.2012.08.020>.
- [75] ATLAS Collaboration, “A detailed map of higgs boson interactions by the atlas experiment ten years after the discovery,” *Nature*, vol. 607, no. 7917, pp. 52–59, 2022. <https://doi.org/10.1038/s41586-022-04893-w>.
- [76] ATLAS Collaboration, “Susy march 2023 summary plot update,” tech. rep., CERN, Geneva, 2023. <https://cds.cern.ch/record/2852738>.
- [77] ATLAS collaboration, “Search for dark matter with the atlas detector at the lhc,” *Journal of Physics: Conference Series*, vol. 798, p. 012100, jan 2017. <https://dx.doi.org/10.1088/1742-6596/798/1/012100>.
- [78] J. Pequenaio, “Computer generated image of the atlas inner detector,” 2008. <https://cds.cern.ch/record/1095926>.
- [79] P. Rosendahl, “Atlas silicon microstrip tracker operation and performance,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 718, pp. 358–360, 2013. Proceedings of the 12th Pisa Meeting on Advanced Detectors.
- [80] ATLAS Collaboration, “Atlas transition radiation tracker (trt): Straw tubes for tracking and particle identification at the large hadron collider,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 845, pp. 257–261, 2017. <https://doi.org/10.1016/j.nima.2016.04.026>.
- [81] A. Andronic and J. P. Wessels, “Transition radiation detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 666, pp. 130–147, 2012. <https://doi.org/10.1016/j.nima.2011.09.041>.
- [82] J. Pequenaio, “Computer generated image of the atlas calorimeter,” 2008. <https://cds.cern.ch/record/1095927>.
- [83] J. Pequenaio, “Computer generated image of the atlas muons subsystem,” 2008. <https://cds.cern.ch/record/1095929>.



- [84] J. Pequeno and P. Schaffner, “How atlas detects particles: diagram of particle paths in the detector,” 2013. <https://cds.cern.ch/record/1505342>.
- [85] ATLAS Collaboration, “Performance of the reconstruction of large impact parameter tracks in the inner detector of atlas,” *The European Physical Journal C*, vol. 83, no. 11, pp. 1–32, 2023. <https://doi.org/10.1140/epjc/s10052-023-12024-6>.
- [86] ATLAS Collaboration, “Electron reconstruction and identification in the atlas experiment using the 2015 and 2016 lh proton–proton collision data at  $\sqrt{s} = 13\text{tev}$ ,” *The European Physical Journal C*, vol. 79, pp. 1–40, 2019. <http://dx.doi.org/10.1140/epjc/s10052-019-7140-6>.
- [87] ATLAS Collaboration, “Calibration and performance of the electromagnetic calorimeter,” tech. rep., CERN, Geneva, 4 2009. <https://cds.cern.ch/record/1171938>.
- [88] R. Frühwirth, “A gaussian-mixture approximation of the bethe–heitler model of electron energy loss by bremsstrahlung,” *Computer Physics Communications*, vol. 154, pp. 131–142, 2003. <https://api.semanticscholar.org/CorpusID:120338890>.
- [89] ATLAS Collaboration, “Electron and photon efficiencies in lh run 2 with the atlas experiment,” *Journal of High Energy Physics*, vol. 2024, no. 5, 2024. [http://dx.doi.org/10.1007/JHEP05\(2024\)16](http://dx.doi.org/10.1007/JHEP05(2024)16).
- [90] ATLAS Collaboration, “Muon reconstruction and identification efficiency in atlas using the full run 2 pp collision data set at  $\sqrt{s} = 13\text{tev}$ ,” *The European Physical Journal C*, vol. 81, p. 578, 2021. <https://doi.org/10.1140/epjc/s10052-021-09233-2>.
- [91] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-kt jet clustering algorithm,” *Journal of High Energy Physics*, vol. 2008, no. 04, p. 063, 2008. <https://doi.org/10.48550/arXiv.0802.1189>.
- [92] ATLAS Collaboration, “Performance of pile-up mitigation techniques for jets in pp collisions at  $\sqrt{s} = 8\text{tev}$  using the atlas detector,” *The European Physical Journal C*, vol. 76, pp. 1–36, 2016. <https://doi.org/10.1140/epjc/s10052-016-4395-z>.
- [93] ATLAS Collaboration, “New techniques for jet calibration with the atlas detector,” *The European Physical Journal C*, vol. 83, no. 8, 2023. <https://doi.org/10.1140/epjc/s10052-023-11837-9>.



- [94] ATLAS Collaboration, “Topological cell clustering in the atlas calorimeters and its performance in lhc run 1,” *The European Physical Journal C*, vol. 77, no. 7, pp. 1–73, 2017. <https://doi.org/10.1140/epjc/s10052-017-5004-5>.
- [95] ATLAS Collaboration, “Machine learning algorithms for b-jet tagging at the atlas experiment,” in *Journal of Physics: Conference Series*, vol. 1085, p. 042031, IOP Publishing, 2018. <https://doi.org/10.48550/arXiv.1711.08811>.
- [96] S. Mondal and L. Mastrolorenzo, “Machine learning in high energy physics: A review of heavy-flavor jet tagging at the lhc,” *The European Physical Journal Special Topics*, 2024. <https://doi.org/10.1140/epjs/s11734-024-01234-y>.
- [97] F. R. Alwall, J. *et al.*, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations,” *J. High Energy Phys.*, vol. 07, no. 7, p. 079, 2014.
- [98] C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, P. Ilten, L. Lönnblad, S. Mrenna, S. Prestel, C. T. Preuss, T. Sjöstrand, P. Skands, M. Utheim, and R. Verheyen, “A comprehensive guide to the physics and usage of pythia 8.3,” *SciPost Phys. Codebases*, vol. 8, 2022. <https://doi.org/10.48550/arXiv.2203.11601>.
- [99] S. Agostinelli, J. Allison, K. a. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, *et al.*, “Geant4—a simulation toolkit,” *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, 2003.
- [100] ATLAS Collaboration, “Atlas athena releases.” <https://atlassoftwaredocs.web.cern.ch/athena/developers/releases/>.
- [101] ATLAS Collaboration, “Software and computing for run 3 of the atlas experiment at the lhc,” *arXiv preprint arXiv:2404.06335*, 2024. <https://doi.org/10.48550/arXiv.2404.06335>.
- [102] ATLAS Experiment at CERN, “Renovating athena: Teaching established software new tricks,” 2024. <https://atlas.cern/updates/briefing/renovating-athena>.
- [103] ATLAS collaboration, “Software performance of the atlas track reconstruction for lhc run 3,” *Computing and Software for Big Science*, vol. 8, 4 2024. <https://doi.org/10.1007/s41781-023-00111-y>.

- [104] ATLAS Collaboration, “Electron efficiency measurements with the atlas detector using 2012 lhc proton–proton collision data,” *The European Physical Journal C*, vol. 77, p. 195, 2017. <https://doi.org/10.1140/epjc/s10052-017-4756-2>.
- [105] ATLAS Collaboration, “Electron reconstruction and identification in the atlas experiment using the 2015 and 2016 lhc proton–proton collision data at  $\sqrt{s} = 13\text{tev}$ ,” *The European Physical Journal C*, vol. 79, 2019. <https://doi.org/10.1140/epjc/s10052-019-7140-6>.
- [106] ATLAS Collaboration, “Electron and photon performance measurements with the atlas detector using the 2015–2017 lhc proton-proton collision data,” *Journal of Instrumentation*, vol. 14, no. 12, pp. P12006–P12006, 2019. <http://dx.doi.org/10.1088/1748-0221/14/12/P12006>.
- [107] R. Hammad, “Electron reconstruction efficiency and scale factors measurements for re-processed Run-2 and early Run-3 data,” tech. rep., CERN, Geneva, 2022. <https://cds.cern.ch/record/2839210>.
- [108] “TagAndProbe Framework.” <https://tagandprobe.readthedocs.io/en/stable/>.
- [109] “TagAndProbe Framework Selections.” [https://tagandprobe.readthedocs.io/en/stable/selection\\_configuration.html](https://tagandprobe.readthedocs.io/en/stable/selection_configuration.html).
- [110] L. Di Ciaccio, K. De Vasconcelos Corga, A. M. Burger, O. Dartsi, C. Diaconu, A. E. Dumitriu, A. Hadeif, F. Hubaut, S. D. Jones, K. Lohwasser, E. Monnier, G. Navarro, A. Petridis, P. Podberezko, P. Pralavorio, E. M. Ruttinger, E. Sauvan, P. Sommer, G. Tarna, and A. Trofymov, “Support Note for Electron ID: efficiency measurements,” Sep 2017. <https://cds.cern.ch/record/2282430>.
- [111] F. Alonso *et al.*, “Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment,” Geneva, Dec 2021. <https://cds.cern.ch/record/2798075>.
- [112] Y. Sulman, “Electron reconstruction efficiency measurements using full Run2 data,” Bucharest, Romania, June 2022. <https://cds.cern.ch/record/2811957>.
- [113] Y. Sulman, “Methodology of electron reconstruction efficiency in situ calibration at high-energy colliders and accuracy of the associated statistical uncertainties,” *Romanian Journal of Physics*, vol. 68, no. 403, 2023. [https://rjp.nipne.ro/2023\\_68\\_5-6/RomJPhys.68.403.pdf](https://rjp.nipne.ro/2023_68_5-6/RomJPhys.68.403.pdf).

- [114] “Egamma Reconstruction Rel22.” <https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/EgammaReconstructionRel22>.
- [115] ATLAS Collaboration, “Atlas software documentation about good run lists.” <https://atlassoftwaredocs.web.cern.ch>.
- [116] “TagAndProbe Framework Commits.”
- [117] ATLAS Collaboration, “Early Inner Detector Tracking Performance in the 2015 data at  $\sqrt{s} = 13$  TeV,” tech. rep., CERN, Geneva, 2015. <https://cds.cern.ch/record/2110140>.
- [118] ATLAS Collaboration, “Modelling of track reconstruction inside jets with the 2016 atlas  $\sqrt{s} = 13$  tev pp dataset,” *CERN, Geneva, Tech. Rep. ATL-PHYS-PUB-2017-016*, 2017. <https://cds.cern.ch/record/2275639>.
- [119] R. Hammad, O. A. Ducu, and J. Maurer, “Rate of fake tracks in dense environments (Rel22/23),” tech. rep., CERN, Geneva, 2023. <https://cds.cern.ch/record/2859907>.
- [120] ATLAS Collaboration, “Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in p p collisions at  $s = 8$  tev with the atlas detector,” *Physical Review D*, vol. 92, no. 7, p. 072004, 2015. <https://doi.org/10.1103/PhysRevD.92.072004>.
- [121] ATLAS Collaboration, “High mass di-jet events,” 2010. [https://atlaspo.cern.ch/public/event\\_display/](https://atlaspo.cern.ch/public/event_display/).
- [122] “ATLAS software documentation.” <https://atlassoftwaredocs.web.cern.ch/trackingTutorial/idooverview/>.
- [123] “Track Selection Criteria.” [https://twiki.cern.ch/twiki/bin/view/AtlasProtected/TrackingCPRecsRun2R22#Selection\\_Criteria](https://twiki.cern.ch/twiki/bin/view/AtlasProtected/TrackingCPRecsRun2R22#Selection_Criteria).
- [124] A. Wharton, W. Yao, and R. Jansky, “Atlas inner detector track quality cuts for run 2,” tech. rep., CERN, Geneva, 2014. <https://cds.cern.ch/record/1752536>.
- [125] R. Brun and F. Rademakers, “Root—an object-oriented data analysis framework,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 389, no. 1-2, pp. 81–86, 1997. [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X).

- [126] O. A. Ducu, “Rate of fake tracks in dense environments: preliminary Rel 22 recommendations, mc20 and Run 2 data,” tech. rep., CERN, Geneva, 2021. <https://cds.cern.ch/record/2780442>.
- [127] CMS Collaboration, “Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at  $\sqrt{s} = 13$  tev,” *J. High Energy Phys.*, vol. 2021, no. 11, p. 153, 2021.
- [128] ATLAS Collaboration, “Search for new phenomena in events with an energetic jet and missing transverse momentum in  $pp$  collisions at  $\sqrt{s} = 13$  tev with the atlas detector,” *Physical Review D*, vol. 103, no. 11, p. 112006, 2021. <https://doi.org/10.1103/PhysRevD.103.112006>.
- [129] A. L. Read, “Presentation of search results: The  $cl_s$  technique,” *Journal of Physics G Nuclear and Particle Physics*, vol. 28, no. 10, pp. 2693–2704, 2002. <https://doi.org/10.1088/0954-3899/28/10/313>.
- [130] J. de Favereau *et al.*, “Delphes 3: a modular framework for fast simulation of a generic collider experiment,” *J. High Energy Phys.*, vol. 02, p. 057, 2014.
- [131] R. D. Ball *et al.*, “Parton distributions for the lhc run 2,” *J. High Energy Phys.*, vol. 04, p. 040, 2015.
- [132] L. Lönnblad and S. Prestel, “Matching tree-level matrix elements with interleaved showers,” *J. High Energy Phys.*, vol. 03, p. 019, 2012.
- [133] L. S. C. S. W. Group, “Susy cross sections at  $\sqrt{s} = 13$  tev.” <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections13TeVgluglu>.
- [134] C. Borschensky *et al.*, “Squark and gluino production cross sections in  $pp$  collisions at  $\sqrt{s} = 13, 14, 33$ , and 100 tev,” *J. High Energy Phys.*, vol. 74, p. 12, 2014. <https://doi.org/10.1140/epjc/s10052-014-3174-y>.
- [135] ATLAS Collaboration, “Search for squarks and gluinos in final states with jets and missing transverse momentum using 139 fb<sup>-1</sup> of  $\sqrt{s} = 13$  tev  $pp$  collision data with the atlas detector,” *J. High Energy Phys.*, vol. 02, p. 143, 2021.
- [136] ATLAS Collaboration, “Jet energy scale measurements and their systematic uncertainties in  $pp$  collisions at  $\sqrt{s} = 13$  tev with the atlas detector,” *Physical Review D*, vol. 09, p. 96, 2017. <https://doi.org/10.1103/PhysRevD.96.072002>.

- [137] I. Lara *et al.*, “Monojet signatures from gluino and squark decays,” *J. High Energy Phys.*, vol. 10, p. 150, 2022.
- [138] H. Rasheed and I. Duminica, “Expanding the gluino exclusion limits using events with one highly energetic final state jet and missing transverse momentum,” *Romanian Journal of Physics*, 2024. Accepted, <https://rjp.nipne.ro/accpaps/79798C4B39DC38E4660C5F9C275B92610519F495.pdf>.
- [139] ATLAS Collaboration, “The quest to discover supersymmetry at the atlas experiment,” *arXiv preprint arXiv:2403.02455*, 2024. <https://doi.org/10.48550/arXiv.2403.02455>.
- [140] ATLAS Collaboration, “Atlas run 2 searches for electroweak production of supersymmetric particles interpreted within the pmssm,” *Journal of High Energy Physics*, vol. 2024, no. 5, pp. 1–57, 2024.
- [141] A. Djouadi *et al.*, “The minimal supersymmetric standard model: Group summary report,” *arXiv preprint hep-ph/9901246*, 1999. <https://doi.org/10.48550/arXiv.hep-ph/9901246>.
- [142] ATLAS Collaboration, “Summary of the atlas experiment’s sensitivity to supersymmetry after lhc run 1—interpreted in the phenomenological mssm,” *Journal of High Energy Physics*, vol. 2015, no. 10, pp. 1–76, 2015. [http://dx.doi.org/10.1007/JHEP10\(2015\)134](http://dx.doi.org/10.1007/JHEP10(2015)134).
- [143] CMS Collaboration, “Phenomenological mssm interpretation of cms searches in pp collisions at  $\sqrt{s} = 7$  and  $8$  tev,” *Journal of High Energy Physics*, vol. 2016, no. 10, 2016. [http://dx.doi.org/10.1007/JHEP10\(2016\)129](http://dx.doi.org/10.1007/JHEP10(2016)129).
- [144] ATLAS Collaboration, “Dark matter interpretations of atlas searches for the electroweak production of supersymmetric particles in  $\sqrt{s} = 8$  tev proton-proton collisions,” *Journal of High Energy Physics*, vol. 175, no. 9, pp. 17500–17543, 2016.
- [145] ATLAS Collaboration, “Simpleanalysis: truth-level analysis framework,” tech. rep., CERN, Geneva, 2022. <https://cds.cern.ch/record/2805991?ln=en>.
- [146] T. Šimko, L. A. Heinrich, C. Lange, A. E. Lintuluoto, D. M. MacDonell, A. Mečionis, D. Rodríguez Rodríguez, P. Shandilya, and V. G. Marco, “Scalable declarative hep analy-

- sis workflows for containerized compute clouds,” *Frontiers in Big Data*, vol. 4, p. 661501, 2021. <https://doi.org/10.3389/fdata.2021.661501>.
- [147] ATLAS Collaboration, “Recast framework reinterpretation of an atlas dark matter search constraining a model of a dark higgs boson decaying to two b-quarks,” in *6th dark matter@LHC 2019 workshop*, 2019. <https://cds.cern.ch/record/2686290?ln=en>.
- [148] K. Cranmer and I. Yavin, “Recast—extending the impact of existing analyses,” *Journal of High Energy Physics*, vol. 2011, no. 4, pp. 1–18, 2011. [http://dx.doi.org/10.1007/JHEP04\(2011\)038](http://dx.doi.org/10.1007/JHEP04(2011)038).
- [149] T. Šimko, L. Heinrich, H. Hirvonsalo, D. Kousidis, and D. Rodríguez, “Reana: A system for reusable research data analyses,” in *EPJ web of conferences*, vol. 214, p. 06034, EDP Sciences, 2019. <https://doi.org/10.1051/epjconf/201921406034>.
- [150] W. Porod, “Sphenos, a program for calculating supersymmetric spectra, susy particle decays and susy particle production at  $e^+e^-$  colliders,” *Computer Physics Communications*, vol. 153, no. 2, pp. 275–315, 2003.
- [151] W. Porod and F. Staub, “Sphenos 3.1: Extensions including flavour, cp-phases and models beyond the mssm,” *Computer Physics Communications*, vol. 183, no. 11, pp. 2458–2469, 2012. <https://doi.org/10.1016/j.cpc.2012.05.021>.
- [152] H. Bahl, T. Hahn, S. Heinemeyer, W. Hollik, S. Paßehr, H. Rzehak, and G. Weiglein, “Precision calculations in the mssm higgs-boson sector with feynhiggs 2.14,” *arXiv preprint arXiv:1811.09073*, 2018. <https://doi.org/10.48550/arXiv.1811.09073>.
- [153] H. Bahl, S. Heinemeyer, W. Hollik, and G. Weiglein, “Reconciling eft and hybrid calculations of the light mssm higgs-boson mass,” *The European Physical Journal C*, vol. 78, no. 1, pp. 1–21, 2018. <http://dx.doi.org/10.1140/epjc/s10052-018-5544-3>.
- [154] H. Bahl and W. Hollik, “Precise prediction for the light mssm higgs-boson mass combining effective field theory and fixed-order calculations,” *The European Physical Journal C*, vol. 76, no. 9, p. 499, 2016. <https://doi.org/10.1140/epjc/s10052-016-4354-8>.
- [155] T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, “High-precision predictions for the light cp-even higgs boson mass of the mssm,” *Physical Review Letters*, vol. 112, no. 14, 2014. <https://doi.org/10.1103/PhysRevLett.112.141801>.

- [156] G. Degrandi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein, “Towards high-precision predictions for the mssm higgs sector,” *The European Physical Journal C-Particles and Fields*, vol. 28, no. 1, pp. 133–143, 2003. <https://doi.org/10.1140/epjc/s2003-01152-2>.
- [157] S. Heinemeyer, W. Hollik, and G. Weiglein, “The masses of the neutral-even higgs bosons in the mssm: Accurate analysis at the two-loop level,” *The European Physical Journal C-Particles and Fields*, vol. 9, no. 2, pp. 343–366, 1999. <https://doi.org/10.1007/s100529900006>.
- [158] S. Heinemeyer, W. Hollik, and G. Weiglein, “Feynhiggs: a program for the calculation of the masses of the neutral cp-even higgs bosons in the mssm,” *Computer Physics Communications*, vol. 124, no. 1, pp. 76–89, 2000.
- [159] D. Barducci, G. Bélanger, J. Bernon, F. Boudjema, J. Da Silva, S. Kraml, U. Laa, and A. Pukhov, “Collider limits on new physics within micromegas<sub>4</sub>. 3,” *Computer Physics Communications*, vol. 222, pp. 327–338, 2018. <https://doi.org/10.48550/arXiv.1606.03834>.
- [160] G. Belanger, A. Mjallal, and A. Pukhov, “Recasting direct detection limits within micromegas and implication for non-standard dark matter scenarios,” *The European Physical Journal C*, vol. 81, no. 3, pp. 1–18, 2021. <https://doi.org/10.1140/epjc/s10052-021-09012-z>.
- [161] F. Mahmoudi, “Superiso v2. 3: A program for calculating flavor physics observables in supersymmetry,” *Computer Physics Communications*, vol. 180, no. 9, pp. 1579–1613, 2009. <https://doi.org/10.1016/j.cpc.2009.02.017>.
- [162] H. Bahl, I. Sobolev, and G. Weiglein, “Precise prediction for the mass of the light mssm higgs boson for the case of a heavy gluino,” *Physics Letters B*, vol. 808, p. 135644, 2020. <https://doi.org/10.1016/j.physletb.2020.135644>.
- [163] K. Peters, “Searches for squarks and gluinos at d0,” *arXiv preprint arXiv:0810.2353*, 2008. <https://arxiv.org/abs/0810.2353>.
- [164] D0 Collaboration, “Search for squarks and gluinos in events with jets and missing transverse energy using  $2.1\text{ fb}^{-1}$  of ppbar collision data at  $\sqrt{s} = 1.96\text{tev}$ ,” *PHYSICS LETTERS B*, vol. 660, no. 5, pp. 449–457, 2008. <http://dx.doi.org/10.1016/j.physletb.2008.01.042>.



- [165] Particle Data Group, “Review of particle physics,” *Progress of Theoretical and Experimental Physics*, vol. 2022, 2022. <https://doi.org/10.1093/ptep/ptac097>.
- [166] LHCb Collaboration, “Measurement of the  $B_s^0 \rightarrow \mu^+ \mu^-$  decay properties and search for the  $B^0 \rightarrow \mu^+ \mu^-$  and  $B_s^0 \rightarrow \mu^+ \mu^- \gamma$  decays,” *Physical Review D*, vol. 105, no. 1, p. 012010, 2022. <http://dx.doi.org/10.1103/PhysRevD.105.012010>.
- [167] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer, and J. Stelzer, “Update of the global electroweak fit and constraints on two-Higgs-doublet models,” *The European Physical Journal C*, vol. 78, no. 8, p. 675, 2018. <http://dx.doi.org/10.1140/epjc/s10052-018-6131-3>.
- [168] CDF Collaboration, “High-precision measurement of the  $W$ -boson mass with the CDF II detector,” *Science*, vol. 376, no. 6589, pp. 170–176, 2022. <https://www.science.org/doi/10.1126/science.abk1781>.
- [169] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group, “Precision electroweak measurements on the  $Z$  resonance,” *Physics Reports*, vol. 427, no. 5–6, pp. 257–454, 2006. <http://dx.doi.org/10.1016/j.physrep.2005.12.006>.
- [170] S. Heinemeyer, W. Hollik, G. Weiglein, and L. Zeune, “Implications of LHC search results on the  $W$  boson mass prediction in the MSSM,” *Journal of High Energy Physics*, vol. 2013, no. 12, p. 084, 2013. [http://dx.doi.org/10.1007/JHEP12\(2013\)084](http://dx.doi.org/10.1007/JHEP12(2013)084).
- [171] Planck Collaboration, “Planck 2018 results. VI. Cosmological parameters,” *Astron. Astrophys.*, vol. 641, p. A6, 2020. <http://dx.doi.org/10.1051/0004-6361/201833910>.
- [172] LZ Collaboration, “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment,” *Physical Review Letters*, vol. 131, 7 2023. <http://dx.doi.org/10.1103/PhysRevLett.131.041002>.
- [173] PICO Collaboration, “Dark Matter Search Results from the Complete Exposure of the PICO-60  $C_3F_8$  Bubble Chamber,” *Physical Review D*, vol. 100, no. 2, p. 022001, 2019. <http://dx.doi.org/10.1103/PhysRevD.100.022001>.
- [174] A. Crivellin, “Effective higgs vertices in the generic mssm,” *Physical Review D—Particles*,



- Fields, Gravitation, and Cosmology*, vol. 83, no. 5, p. 056001, 2011. <https://doi.org/10.1103/PhysRevD.83.056001>.
- [175] J. Erler and P. Langacker, “Electroweak model and constraints on new physics,” *arXiv preprint hep-ph/0407097*, 2004. <https://doi.org/10.48550/arXiv.hep-ph/0407097>.
  - [176] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, “Madgraph 5: going beyond,” *Journal of High Energy Physics*, vol. 2011, no. 6, pp. 1–40, 2011.
  - [177] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. 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,” *Journal of High Energy Physics*, vol. 2014, no. 7, pp. 1–157, 2014.
  - [178] 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,” *Computer physics communications*, vol. 191, pp. 159–177, 2015. <https://doi.org/10.1016/j.cpc.2015.01.024>.
  - [179] L. Heinrich, M. Feickert, G. Stark, and K. Cranmer, “pyhf: pure-python implementation of histfactory statistical models,” *Journal of Open Source Software*, vol. 6, no. 58, p. 2823, 2021. <https://arxiv.org/abs/2211.15838>.
  - [180] F. Brümmer, S. Kraml, and S. Kulkarni, “Anatomy of maximal stop mixing in the mssm,” *Journal of High Energy Physics*, vol. 2012, no. 8, pp. 1–34, 2012.
  - [181] M. Carena, D. Garcia, U. Nierste, and C. E. Wagner, “ $b \rightarrow s\gamma$  and supersymmetry with large  $\tan\beta$ ,” *Physics Letters B*, vol. 499, no. 1-2, pp. 141–146, 2001. [http://dx.doi.org/10.1016/S0370-2693\(01\)00009-0](http://dx.doi.org/10.1016/S0370-2693(01)00009-0).
  - [182] ATLAS Collaboration, “Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum in pp collisions at  $\sqrt{s} = 13\text{TeV}$  with the atlas detector,” *Physical Review D*, vol. 104, no. 11, p. 112010, 2021. <https://doi.org/10.1103/PhysRevD.104.112010>.
  - [183] ATLAS Collaboration, “Search for direct production of electroweakinos in final states with missing transverse momentum and a higgs boson decaying into photons in pp collisions at  $\sqrt{s} = 13\text{TeV}$  with the atlas detector,” *Journal of high energy physics*, vol. 2020, no. 10, pp. 1–46, 2020.

- [184] ATLAS Collaboration, “Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in  $\sqrt{s} = 13\text{tev}$  pp collisions using the atlas detector,” *The European Physical Journal C*, vol. 80, no. 2, 2020. <http://dx.doi.org/10.1140/epjc/s10052-019-7594-6>.
- [185] ATLAS Collaboration, “Searches for new phenomena in events with two leptons, jets, and missing transverse momentum in  $139\text{ fb}^{-1}$  of  $\sqrt{s} = 13\text{tev}$  pp collisions with the atlas detector,” *The European Physical Journal C*, vol. 83, p. 515, 2023. <https://doi.org/10.1140/epjc/s10052-023-11434-w>.
- [186] ATLAS Collaboration, “Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in  $\sqrt{s} = 13\text{tev}$  pp collisions with the atlas detector,” *The European Physical Journal C*, vol. 81, no. 12, 2021. <https://doi.org/10.1140/epjc/s10052-021-09749-7>.
- [187] ATLAS Collaboration, “Search for supersymmetry in events with four or more charged leptons in  $139\text{ fb}^{-1}$  of  $\sqrt{s} = 13\text{tev}$  pp collisions with the atlas detector,” *Journal of High Energy Physics*, vol. 2021, no. 7, p. 167, 2021.
- [188] ATLAS Collaboration, “Searches for electroweak production of supersymmetric particles with compressed mass spectra in  $\sqrt{s} = 13\text{tev}$  pp collisions with the atlas detector,” *Physical review D*, vol. 101, no. 5, p. 052005, 2020. <https://doi.org/10.1103/PhysRevD.101.052005>.
- [189] ATLAS Collaboration, “Search for long-lived charginos based on a disappearing-track signature using  $136\text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 13\text{tev}$  with the atlas detector,” *The European physical journal. C, Particles and fields*, vol. 82, no. 7, p. 606, 2022. <https://doi.org/10.1140/epjc/s10052-022-10489-5>.
- [190] ATLAS Collaboration, “Search for squarks and gluinos in final states with one isolated lepton, jets, and missing transverse momentum at  $\sqrt{s} = 13\text{tev}$  with the atlas detector,” *The European Physical Journal C*, vol. 81, no. 7, 2021. <https://doi.org/10.1140/epjc/s10052-021-09344-w>.
- [191] ATLAS Collaboration, “Search for pair production of squarks or gluinos decaying via sleptons or weak bosons in final states with two same-sign or three leptons with the atlas detector,” *Journal of High Energy Physics*, vol. 2024, no. 2, pp. 1–55, 2024.

- [192] ATLAS Collaboration, “Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using  $\sqrt{s} = 13\text{tev}$  proton-proton collisions recorded by atlas in run 2 of the lhcb,” *Journal of High Energy Physics*, vol. 2020, no. 10, 2020.
- [193] ATLAS Collaboration, “Search for squarks and gluinos in final states with jets and missing transverse momentum using 139  $fb^{-1}$  of  $\sqrt{s} = 13\text{ tev}$  pp collision data with the atlas detector,” *Journal of High Energy Physics*, vol. 2021, no. 2, 2020.
- [194] ATLAS Collaboration, “Combination of searches for invisible decays of the higgs boson using 139 $fb^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13\text{tev}$  collected with the atlas experiment,” *Physics Letters. B*, vol. 842, 2023. <http://dx.doi.org/10.1016/j.physletb.2023.137963>.
- [195] ATLAS Collaboration, “Combined measurements of higgs boson production and decay using up to 80  $fb^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13\text{tev}$  collected with the atlas experiment,” *Physical review D*, vol. 101, 2020. <https://doi.org/10.1103/PhysRevD.101.012002>.
- [196] ATLAS Collaboration, “Search for heavy higgs bosons decaying into two tau leptons with the atlas detector using pp collisions at  $\sqrt{s} = 13\text{tev}$ ,” *Physical review letters*, vol. 125, no. 5, 2020. <https://doi.org/10.1103/PhysRevLett.125.051801>.
- [197] R. V. Harlander, S. Liebler, and H. Mantler, “Sushi: A program for the calculation of higgs production in gluon fusion and bottom-quark annihilation in the standard model and the mssm,” *Computer Physics Communications*, vol. 184, no. 6, pp. 1605–1617, 2013. <https://doi.org/10.1016/j.cpc.2013.02.006>.
- [198] “pMSSM Model generation Framework.” <https://gitlab.cern.ch/atlas-phys-susy-wg/summaries/pmssm/pmssm-model-generation>.
- [199] “pMSSMFactory Framework.” <https://gitlab.cern.ch/atlas-phys-susy-wg/summaries/pmssm/pMSSMFactory>.

# List of Figures

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                     |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1  | Loop Feynman diagram example which corrects Higgs mass <a href="#">[4]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                | 14 |
| 2.2  | SUSY processes cross-section at $\sqrt{s} = 13$ TeV <a href="#">[40]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                  | 18 |
| 2.3  | Strong production of SUSY at LHC . . . . .                                                                                                                                                                                                                                                                                                                                                                                          | 19 |
| 2.4  | Electroweak production of SUSY at LHC . . . . .                                                                                                                                                                                                                                                                                                                                                                                     | 20 |
| 2.5  | Observed and expected exclusion limits on SUSY simplified models for chargino-pair production with W-boson-mediated decays in Chargino vs Neutralino plane <a href="#">[46]</a> . . . . .                                                                                                                                                                                                                                           | 21 |
| 3.1  | Aerial view of LHC at CERN <a href="#">[56]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                                           | 26 |
| 3.2  | LHC and HL-LHC Schedule as of 5 Dec 2014 <a href="#">[57]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                             | 27 |
| 3.3  | Overview of complex experimental accelerators at CERN <a href="#">[58]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                | 28 |
| 3.4  | (a) illustrates the total integrated luminosity provided to the LHC, depicted in green, with ATLAS-recorded luminosity shown in yellow, and the portion deemed suitable for physics analyses displayed in blue, covering full Run 2. (b) presents the luminosity-weighted distribution of the average number of interactions per bunch crossing throughout Run 2. Both figures are sourced from Ref. <a href="#">[63]</a> . . . . . | 30 |
| 3.5  | (a) illustrates the total integrated luminosity delivered by the LHC for the first two years and ongoing third year of Run 3 (b) presents the luminosity-weighted distribution of the average number of interactions per bunch crossing for the first two years and ongoing third year of Run 3. Both figures are sourced from Ref. <a href="#">[64]</a> . . . . .                                                                  | 30 |
| 3.6  | Computer generated picture of ATLAS detector showing its different parts of ATLAS detector taken from reference <a href="#">[65]</a> . . . . .                                                                                                                                                                                                                                                                                      | 31 |
| 3.7  | General view of different components of ATLAS detector by layers. . . . .                                                                                                                                                                                                                                                                                                                                                           | 34 |
| 3.8  | Computer generated image of ATLAS Inner Detector taken from reference <a href="#">[78]</a> . . . . .                                                                                                                                                                                                                                                                                                                                | 35 |
| 3.9  | Computer generated picture of ATLAS Calorimeters <a href="#">[82]</a> . . . . .                                                                                                                                                                                                                                                                                                                                                     | 36 |
| 3.10 | Computer generated picture of ATLAS Calorimeters Muon Spectrometer <a href="#">[83]</a> . . . . .                                                                                                                                                                                                                                                                                                                                   | 38 |
| 3.11 | Computer generated picture of particle paths in the ATLAS detector <a href="#">[84]</a> . . . . .                                                                                                                                                                                                                                                                                                                                   | 40 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                               |    |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.12 | A diagram depicting the electron’s journey through the ECAL and different sections of the ID within the ATLAS detector. The red line represents a hypothetical electron path, beginning in the tracking system before passing into the ECAL. The dashed red line illustrates the path of a photon generated from the electron’s interaction with the material in the tracking system [86]. . . . .                                                            | 42 |
| 3.13 | The evolution of a partonic jet from hard scattering to hadronization, forming particle jets, which are then measured as calorimeter jets in the ATLAS detector. The calorimeter detects energy deposits in both the calorimeters [52]. . . . .                                                                                                                                                                                                               | 45 |
| 3.14 | A parton-level Monte Carlo simulated event sample that shows the regions and forms of the hard jets that result for $R = 1$ , taken from Ref. [91]. . . . .                                                                                                                                                                                                                                                                                                   | 46 |
| 3.15 | The jet energy response as a function of $\eta_{det}$ for jets of truth energy of 30, 50, 110, 500, and 1200 GeV [93]. . . . .                                                                                                                                                                                                                                                                                                                                | 47 |
| 3.16 | Various measurements of the total and fiducial production cross-sections under the Standard Model, together with a comparison of the measurements to the theoretical values, are summarised [69]. . . . .                                                                                                                                                                                                                                                     | 52 |
| 4.1  | Invariant mass distributions of electron pairs in the denominator of equation 4.2 by taking failing Quality Track term and photon term(a) and the numerator(b) of the reconstruction efficiency. Background templates are normalized, and their variation1 is used, given in Table 4.5. . . . .                                                                                                                                                               | 60 |
| 4.2  | The plots a(b) for the 2015+16 data, c(d) for the 2017 data, and e(f) for the 2018 data, show the comparison between the data efficiency and MC efficiency in the low $E_T$ range, $15 < E_T < 20$ GeV, and in the high $E_T$ range, $80 < E_T < 150$ GeV. The lower panel illustrates the <b>Scale Factors</b> for the respective bins. The error bars reflect the total uncertainties, incorporating both statistical and systematic contributions. . . . . | 66 |
| 4.3  | The plots for 2015+16 data where the first and second plot shows the overview of the data and MC efficiencies as a function of $E_T$ and $\eta$ bins (where $\eta_{primary\ cluster\ BE2}$ refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of $E_T$ and $\eta$ . . . . .                                    | 67 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                      |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.4  | The plots for 2017 data where the first and second plot shows the data and <b>MC</b> efficiencies as a function of $E_T$ and $\eta$ bins (where $\eta_{primary\ cluster\ BE2}$ refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of $E_T$ and $\eta$ . . . . .       | 68 |
| 4.5  | The plots for 2018 data where the first and second plot shows the data and MC efficiencies as a function of $E_T$ and $\eta$ bins (where $\eta_{primary\ cluster\ BE2}$ refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of $\eta$ ) respectively, while the third plot shows the same trend of scale factors in all bins of $E_T$ and $\eta$ . . . . .              | 69 |
| 4.6  | The first and second plot shows the overview of the comparison of data and mc efficiencies between rel21 and rel22 as a function of $E_T$ and $\eta$ for $15 < E_T < 150\text{GeV}$ respectively while the third plot shows the same trend of scale factors all bins of $E_T$ and $\eta$ . . . . .                                                                                                                   | 70 |
| 4.7  | The plots a(b) for early Run 3 data depict the comparison between data efficiency and MC efficiency in the low $E_T$ range, $15 < E_T < 20\text{ GeV}$ , and the high $E_T$ range, $80 < E_T < 150\text{ GeV}$ . The bottom panel shows the <b>Scale Factors</b> for the corresponding bins. Error bars indicate the total uncertainties, including statistical and systematic components. . . . .                   | 71 |
| 4.8  | The plots for early run3 data where the first two plots show the overview of the data and MC efficiencies as a function of $E_T$ and $\eta$ bins (where $\eta_{primary\ cluster\ BE2}$ refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of $\eta$ ), respectively, while the third plot shows the same trend of scale factors all bins of $E_T$ and $\eta$ . . . . . | 73 |
| 4.9  | The plots make a comparison for early run3 data with data from 2018 where the first and second plot shows the overview comparison of the data and MC efficiencies as a function of $E_T$ and $\eta$ bins, respectively while the third plot shows the same trend of scale factors all bins of $E_T$ and $\eta$ . . . . .                                                                                             | 74 |
| 4.10 | The plots compare the scale factors for early run3 data with run3 pre-recommendations as a function of $E_T$ and $\eta$ bins. . . . .                                                                                                                                                                                                                                                                                | 75 |
| 4.11 | The plots compare the MC efficiencies for early run3 with silicon hits $\geq 7$ and silicon hits $\geq 8$ as a function of $E_T$ and $\eta$ bins where $\eta_{primary\ cluster\ BE2}$ refers to the “bi-centre” of the cluster to the second layer of the calorimeter in the direction of $\eta$ . . . . .                                                                                                           | 75 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |    |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 5.1 | Graphical representation of a proton-proton collision featuring a high-mass dijet event captured during LHC Run 1 in 2010 [121]. . . . .                                                                                                                                                                                                                                                                                                                                                                      | 79 |
| 5.2 | (a) Rate of fake tracks as a function of the average number of interactions per bunch crossing $\langle\mu\rangle$ . (b) Rate of fake tracks as a function of the number of tracks inside a jet. Distributions obtained in MC simulation for several $\Delta R(\text{jet}, \text{tracks})$ intervals. The plots include $\Delta R(\text{jet}, \text{track})$ thresholds of 0.05 (red), 0.1 (blue), 0.15 (purple), and 0.2 (green). Only the statistical uncertainties are shown. . . .                        | 80 |
| 5.3 | Illustration of the geometric parameters used to describe the track of a charged particle in the ATLAS detector. The particle's path is represented by a curved line, indicating its trajectory under the influence of the detector's magnetic field. The closest point on the particle's path to the beam spot position is where the particle comes nearest to it [122]. . . . .                                                                                                                             | 82 |
| 5.4 | Distributions for LooseWP after the pre-selection. The top left and bottom left plots show the leading and sub-leading jet $\eta$ distributions, respectively. The top right and bottom right plots show the leading and sub-leading jet $p_T$ distributions, respectively. Black dots represent data points, and green up-triangles represent MC for all tracks. The ratio plots beneath each distribution compare the data to MC, with the last bin in each distribution including overflow events. . . . . | 87 |
| 5.5 | Distributions for LooseWP following the pre-selection. The plot on the left displays the number of jets, while the right plot illustrates the number of tracks in the jet. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events. . . . .                                                   | 88 |
| 5.6 | Distributions for LooseWP after the pre-selection. The left plot shows the distribution of the number of pixel hits, while the right plot shows the distribution of the number of pixel holes. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events. . . . .                               | 88 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |    |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 5.7  | Distributions for <b>LooseWP</b> after the pre-selection. The top left plot shows the distribution of the number of SCT hits, the top right plot shows the distribution of the number of SCT holes, and the bottom left plot shows the distribution of the number of SCT shared hits. The bottom right plot shows the distribution of the combined number of TRT outliers and TRT hits. The results are shown for data (black dots), and MC contribution is either inclusively or split into separate real/fake track components. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in both distributions including overflow events. . . . .                                                                | 89 |
| 5.8  | Distributions for <b>LooseWP</b> of the track $\chi^2/\text{DOF}$ variable after pre-selection, shown for both data and MC simulation. The final bin accounts for overflow. The hashed magenta region in the lower panel indicates the MC statistical uncertainty.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 90 |
| 5.9  | Distributions for <b>LooseWP</b> defined fake enriched CR. The top left plot shows the distribution of the track transverse impact parameter ( $d_0$ ), and the top right plot shows the distribution of sin of the theta angle multiplied by the track longitudinal impact parameter computed with respect to the primary vertex. The bottom plot shows the distribution of the track $\chi^2/\text{DOF}$ . The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalised to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events. . . . . | 91 |
| 5.10 | Distributions for <b>LooseWP</b> defined fake enriched CR. The top left plot shows the distribution of the number of pixel hits, and the top right plot shows the distribution of the number of SCT hits. The bottom plot shows the distribution of the number of TRT Outliers plus TRT hits. The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalised to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events. . . . .                                                                                                                | 92 |
| 5.11 | The distribution for <b>LooseWP</b> of the truth-reco track matching probability after the pre-selection (black dots) and after each requirement used to define the control region enriched in fake track (coloured markers). Distribution obtained with MC simulation. Only the statistical uncertainties are shown. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                     | 93 |



|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.12 | The good performance of the fit (red line) in the control region enriched in fake track for <b>LooseWP</b> . Data (back dots), MC real tracks (blue down-triangles), and MC fake track (magenta squares) distributions are also shown. The last bin includes overflow. Only the statistical uncertainties are considered. . . . .                                                                                                                                                              | 94  |
| 5.13 | <b>LooseWP</b> . Data & MC simulation $\chi^2/n_{\text{DOF}}$ when varying the fraction of fake tracks “f” in the CR. The fit results (Maximum Likelihood Estimation of the fraction of fake tracks) are also shown with coloured dots. . . . .                                                                                                                                                                                                                                                | 95  |
| 5.14 | Overall uncertainties in the fake track fraction modelling determined in separate bins of $\langle \mu \rangle$ , compared to the inclusive measurement. . . . .                                                                                                                                                                                                                                                                                                                               | 98  |
| 5.15 | Overall uncertainties in the fake track fraction modelling determined from each selected variable in separate bins of $\langle \mu \rangle$ , compared to the inclusive measurement. . . . .                                                                                                                                                                                                                                                                                                   | 98  |
| 6.1  | A generic Feynman diagram for the pair production of gluinos with the decay mode of $\tilde{g} \rightarrow \bar{q} + q + \tilde{\chi}_1^0$ and a jet from initial-state radiation is indicated as illustration purposes. . . . .                                                                                                                                                                                                                                                               | 103 |
| 6.2  | Exclusion region at 95 % <b>CL</b> as a function of $m_{\tilde{g}}$ and $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ mass difference for $\tilde{g}\tilde{g}$ production. The region below 1000 GeV is excluded. Mass differences below 5 GeV are not considered because gluinos become long-lived particles and can hadronize, with non-trivial consequences on production details and interactions with the detector. The dashed lines around observed limits indicated the uncertainties. . . . . | 104 |
| 6.3  | Relative jet momentum resolution as a function of $p_T$ , for central jets. The expectation from the Monte Carlo simulation based on DELPHES and used in this paper is compared with the best fit of a common jet momentum resolution parameterisation. . . . .                                                                                                                                                                                                                                | 105 |
| 7.1  | Process for the pMSSM scan, starting from sampling the parameter space to evaluating whether each model is excluded [140]. . . . .                                                                                                                                                                                                                                                                                                                                                             | 111 |
| 7.2  | Quark self-energy with squark and gluino as virtual particles [174]. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                   | 113 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 7.3  | Distribution of the LSP mass for the General scan. (a) The distribution of all general models considered, both before and after the application of ATLAS Run 2 constraints, with the blue dashed line indicating the moderately excluded strains applied. (b) The distribution of all General scan models prior to any constraints, the remaining models after applying all external constraints, after applying both external constraints and the ATLAS Higgs Run 2 constraints, and finally after applying all external and ATLAS Run 2 constraints. The lower panels display the fraction of models excluded in each scenario. . . . .                                                                                      | 121 |
| 7.4  | Fraction of General scan models excluded by the ATLAS Run 2 SUSY results with Strong production. The first column, (a) (c) (e), shows the $m(\tilde{g})$ vs. $m(\tilde{\chi}_1^0)$ plane and the second column, (b) (d) (f), shows the $m(\tilde{q})$ vs. $m(\tilde{\chi}_1^0)$ plane. The first row includes all models. The second includes all models that pass all external constraints, and the third-row models pass the external constraints and ATLAS Higgs searches. . . . .                                                                                                                                                                                                                                          | 123 |
| 7.5  | Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. Figure(a) shows the $m(\tilde{g})$ vs. $m(\tilde{q})$ plane includes all models, (b) includes all models that pass all external constraints, and (c) includes models that pass the external constraints and ATLAS Higgs searches. . . . .                                                                                                                                                                                                                                                                                                                                                                                                     | 124 |
| 7.6  | Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. The first column, (a) (c) (e), shows the $m(\tilde{q}_L)$ vs. $m(\tilde{\chi}_1^0)$ plane and the second column, (b) (d) (f), shows the $m(\tilde{q}_R)$ vs. $m(\tilde{\chi}_1^0)$ plane. The first row includes all models, the second includes all models that pass all external constraints and the third row models that pass the external constraints and ATLAS Higgs searches. (a), (c), and (e) only consider the models with the first two generations of left-handed squark as the lightest squark. (b), (d), and (f) only consider the models with the first two generations of right-handed squark as the lightest squark. . . . . | 126 |
| 7.7  | Distribution of branching ratios (BR) for various decay modes of $\tilde{g}$ in the pMSSM General Scan. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 128 |
| 7.8  | Distribution of branching ratios (BR) for various decay modes of $\tilde{q}_L$ in the pMSSM General Scan. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 129 |
| 7.9  | Distribution of branching ratios (BR) for various decay modes of $\tilde{q}_R$ in the pMSSM General Scan. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 130 |
| 7.10 | Fraction of General scan models excluded by the ATLAS Run 2 SUSY Strong results. The first column, (a) (c) (e), shows the $m(\tilde{t})$ vs. $m(\tilde{\chi}_1^0)$ plane, and the second column, (b) (d) (f), shows the $m(\tilde{b})$ vs. $m(\tilde{\chi}_1^0)$ plane. The first . . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                    |     |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |     |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B.2 | Distributions for <b>TightPrimaryWP</b> following the pre-selection. The plot on the left displays the number of jets, while the right plot illustrates the number of tracks in the jet. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events. . . . .                                                                                                                                                                                                                                                                                | 172 |
| B.3 | Distributions for <b>TightPrimaryWP</b> after the pre-selection. The left plot shows the distribution of the number of pixel hits, while the right plot shows the distribution of the number of pixel holes. Results are presented for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). The ratio plots below each distribution compare the data with MC-all, with the final bin in both plots including overflow events. . . . .                                                                                                                                                                                                                                                            | 172 |
| B.4 | Distributions for <b>TightPrimaryWP</b> after the pre-selection. The top left plot shows the distribution of the number of SCT hits, the top right plot shows the distribution of the number of SCT holes, and the bottom left plot shows the distribution of the number of SCT shared hits. The bottom right plot shows the distribution of the combined number of TRT outliers and TRT hits. The results are shown for data (black dots), and MC contribution is either inclusively or split into separate real/fake track components. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in both distributions including overflow events. . . . .                                                                | 173 |
| B.5 | Distributions for <b>TightPrimaryWP</b> of the track $\chi^2/\text{DOF}$ variable after pre-selection, shown for both data and MC simulation. The final bin accounts for overflow. The hashed magenta region in the lower panel indicates the MC statistical uncertainty.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 174 |
| B.6 | Distributions for <b>TightPrimaryWP</b> defined fake enriched CR. The top left plot shows the distribution of the track transverse impact parameter ( $d_0$ ), and the top right plot shows the distribution of sin of the theta angle multiplied by the track longitudinal impact parameter computed with respect to the primary vertex. The bottom plot shows the distribution of the track $\chi^2/\text{DOF}$ . The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalized to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events. . . . . | 175 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B.7 | Distributions for <b>TightPrimaryWP</b> defined fake enriched CR. The top left plot shows the distribution of the Number of pixel hits, and the top right plot shows the distribution of the Number of SCT hits. The bottom plot shows the distribution of the Number of TRT Outliers plus TRT hits. The results are shown for data (black dots), MC-all (green up-triangles), MC-real (blue down-triangles), and MC-fake (purple squares). All MC distributions are normalized to data. The ratio plots beneath each distribution compare the data to MC-all, with the last bin in all distributions, including overflow events. . . . . | 176 |
| B.8 | The good performance of the fit (red line) in the CR enriched in fake tracks. Data (black dots), MC real tracks (blue down-triangles) and MC fake tracks (magenta squares) distributions are also shown. The last bin includes overflow. Only the statistical uncertainties are considered. . . . .                                                                                                                                                                                                                                                                                                                                       | 177 |
| B.9 | <b>TightPrimaryWP</b> . Data & MC simulation $\chi^2/\text{DOF}$ when varying the fraction of fake tracks “f” in the CR. The fit results (Maximum Likelihood Estimation of the fraction of fake tracks) are also shown with coloured dots. . . . .                                                                                                                                                                                                                                                                                                                                                                                        | 178 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |     |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| C.1 | Analysis of $M_1$ Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario. . . . . | 186 |
| C.2 | Analysis of $M_2$ Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario. . . . . | 186 |
| C.3 | Analysis of $M_3$ Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario. . . . . | 187 |
| C.4 | Analysis of $\mu$ Distribution in the General Scan. (a) Displays the distribution for all considered general models both before and after the enforcement of the ATLAS (Higgs) Run 2 constraints. (b) Illustrates the distribution for all initial general models, the subset of models that persist after all external constraints, those remaining after the application of both external and ATLAS Higgs Run 2 constraints, and finally, those that remain subsequent to the imposition of all external constraints alongside the ATLAS Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario. . . . . | 187 |
| C.5 | Proportion of General Scan Models Eliminated by ATLAS Run 2 SUSY Outcomes with Strong and EWK Production Illustrated on the $M_1$ vs. $M_2$ Plane. Figure (a) encompasses all models, (b) encompasses models that withstand all external constraints, (c) encompasses models that withstand both the external constraints and the ATLAS Higgs Run 2 constraints. The lower panels depict the proportion of models that are excluded in each scenario. . . . .                                                                                                                                                                                              | 188 |

# List of Tables

|     |                                                                                                                                                                                                                                                                                                                                                 |    |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1 | Fundamental building blocks in the domain of Elementary Particle Physics that correspond to the Standard Model <a href="#">[9]</a> . . . . .                                                                                                                                                                                                    | 6  |
| 2.2 | Comparison of the SM particles with their Supersymmetric partners concerning their spins. . . . .                                                                                                                                                                                                                                               | 15 |
| 2.3 | Particles introduced by the MSSM, except $h^0$ , are shown in terms of their gauge and mass eigenstates. The gauge eigenstates refer to the particle states before electroweak symmetry breaking, while the mass eigenstates correspond to the physical particles after electroweak symmetry breaking. . . . .                                  | 16 |
| 2.4 | Overview of the 19D phenomenological Minimal Supersymmetric Standard Model                                                                                                                                                                                                                                                                      | 23 |
| 4.1 | Measurement bins in electron transverse energy $E_T$ . . . . .                                                                                                                                                                                                                                                                                  | 56 |
| 4.2 | Measurement bins in electron pseudo-rapidity $\eta$ . . . . .                                                                                                                                                                                                                                                                                   | 56 |
| 4.3 | Triggers used for the measurements. . . . .                                                                                                                                                                                                                                                                                                     | 57 |
| 4.4 | Object level selections for <b>tag</b> and <b>probe</b> system . . . . .                                                                                                                                                                                                                                                                        | 59 |
| 4.5 | Templates used for background estimation for electrons with track . . . . .                                                                                                                                                                                                                                                                     | 61 |
| 5.1 | Efficiency and Fake Track Fraction for <b>LooseWP</b> and <b>TightPrimaryWP</b> working points, based on MC simulation with an average pile-up of $\langle\mu\rangle = 40$ in $t\bar{t}$ events <a href="#">[124]</a> . . . . .                                                                                                                 | 85 |
| 5.2 | Summary of variables and their requirements for defining the control region enriched in fake track. . . . .                                                                                                                                                                                                                                     | 86 |
| 5.3 | Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), ratio between the number of fake and real tracks ( $F_{\text{trk}}/R_{\text{trk}}$ in the simulation) and the selection efficiency of each criterion ( $\epsilon$ ) in data and MC simulation for the <b>LooseWP</b> . . . . .                                                  | 93 |
| 5.4 | <b>LooseWP</b> . The fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) along with the corresponding statistical uncertainty after fitting the chosen distributions. The outcomes of the 1000 toy experiments and the minima of the $\chi^2/n_{\text{DOF}}$ from the data and MC histograms of these variables are presented. . . . . | 95 |

|     |                                                                                                                                                                                                                                                                                                                                                        |     |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.5 | Fraction of fake tracks at the pre-selection level for the <b>LooseWP</b> . The parameter $f^{\text{fakeTrk}}$ is derived from the fit of the selected distributions. The table compares the fraction of fake tracks in data and MC and their relative difference. . . . .                                                                             | 97  |
| 5.6 | Fraction of fake tracks at the pre-selection level for the <b>LooseWP</b> . The parameter $f^{\text{fakeTrk}}$ is derived from the toy experiments. The table compares the fraction of fake tracks in data and MC and their relative difference. . . . .                                                                                               | 97  |
| 5.7 | Fraction of fake tracks at the pre-selection level for the <b>LooseWP</b> . The parameter $f^{\text{fakeTrk}}$ is derived from the histogram $\chi^2/\text{DOF}$ . The table compares the fraction of fake tracks in data and MC and their relative difference. . . . .                                                                                | 97  |
| 6.1 | Illustration of Signal Region bins for increasing cuts on $E_T^{\text{miss}}$ [128] . . . . .                                                                                                                                                                                                                                                          | 102 |
| 6.2 | Selection criteria for signal region events . . . . .                                                                                                                                                                                                                                                                                                  | 103 |
| 7.1 | Summary of software tools and their versions used to analyse the pMSSM model. Each program is responsible for specific calculations. . . . .                                                                                                                                                                                                           | 110 |
| 7.2 | External constraints from flavour physics observables, electroweak precision measurements, and Dark Matter searches [140]. . . . .                                                                                                                                                                                                                     | 112 |
| 7.3 | Parameter ranges which are randomly sampled for the General scan. . . . .                                                                                                                                                                                                                                                                              | 117 |
| 7.4 | Set-ups for the pMSSM General Scan and Models Passing Each Step. . . . .                                                                                                                                                                                                                                                                               | 117 |
| 7.5 | List of ATLAS searches considered in this analysis. . . . .                                                                                                                                                                                                                                                                                            | 119 |
| A.1 | The datasets used for the electron reconstruction efficiency measurements with data and MC for complete Run2, i.e. for the years 2015+2016, 2017, and 2018 .                                                                                                                                                                                           | 160 |
| A.2 | The datasets used for comparing rel21 and rel22 efficiencies and scale factors. . .                                                                                                                                                                                                                                                                    | 160 |
| A.3 | The datasets used to measure early Run 3 electron reconstruction efficiency and scale factors. . . . .                                                                                                                                                                                                                                                 | 161 |
| B.1 | Data Samples used in the Fake Track Studies Measurements . . . . .                                                                                                                                                                                                                                                                                     | 170 |
| B.2 | Monte Carlo simulated samples used in the Fake Track Studies Measurements .                                                                                                                                                                                                                                                                            | 170 |
| B.3 | <b>TightPrimaryWP</b> . The fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ) along with the corresponding statistical uncertainty after fitting the chosen distributions. The outcomes of the 1000 toy experiments and the minima of the $\chi^2/n_{\text{DOF}}$ from the data and MC histograms of these variables are presented. . . . . | 178 |
| B.4 | Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the <b>LooseWP</b> . . . . .                                                           | 179 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                               |     |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B.5  | <b>LooseWP.</b> Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the $\chi^2/\text{DOF}$ of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column. . . . . | 179 |
| B.6  | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the fit of the selected distributions. . . . .                                                                                                                                                                                                                         | 180 |
| B.7  | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the toys experiment. . . . .                                                                                                                                                                                                                                           | 180 |
| B.8  | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the histogram $\chi^2/\text{DOF}$ . . . . .                                                                                                                                                                                                                            | 180 |
| B.9  | Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the <b>LooseWP</b> . . . . .                                                                                                                                  | 181 |
| B.10 | <b>LooseWP.</b> Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the $\chi^2/\text{DOF}$ of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column. . . . . | 181 |
| B.11 | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the fit of the selected distributions. . . . .                                                                                                                                                                                                                         | 182 |
| B.12 | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the toys experiment. . . . .                                                                                                                                                                                                                                           | 182 |
| B.13 | <b>LooseWP.</b> Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken from the histogram $\chi^2/\text{DOF}$ . . . . .                                                                                                                                                                                                                            | 182 |
| B.14 | Number of tracks in data ( $N_{\text{tracks}}^{\text{data}}$ ), the ratio between the number of fake and real tracks ( $\frac{F_{\text{trk}}}{R_{\text{trk}}}$ ) and the selection efficiency of each criterion ( $\varepsilon$ ) in data and MC simulation for the <b>LooseWP</b> . . . . .                                                                                                                                  | 183 |
| B.15 | <b>LooseWP.</b> Fraction of fake tracks ( $f_{\text{CR}}^{\text{fakeTrk}}$ ), and the associated statistical uncertainty obtained after fitting the selected distributions. The results of the 1000 toys experiment are shown in the third column. The minima of the $\chi^2/\text{DOF}$ of the data and MC histograms of these variables are shown ( $f_{\chi^2/\text{DOF}}^{\text{fakeTrk}}$ ) in the third column. . . . . | 183 |



|                                                                                                                                                 |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B.16 LooseWP. Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken |     |
| from the fit of the selected distributions. . . . .                                                                                             | 184 |
| B.17 LooseWP. Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken |     |
| from the toys experiment. . . . .                                                                                                               | 184 |
| B.18 LooseWP. Fraction of fake tracks at pre-selection level, $f_{\text{pre-Sel}}^{\text{fakeTrk}}$ . $f_{\text{CR}}^{\text{fakeTrk}}$ is taken |     |
| from the histogram $\chi^2/\text{DOF}$ . . . . .                                                                                                | 184 |

