

MANFREDI RONZANI

SUSY IN STRONG PRODUCTION: SEARCH FOR SUSY  
IN FINAL STATES WITH JETS AND MISSING TRANS-  
VERSE MOMENTUM WITH THE ATLAS DETECTOR





# SUSY IN STRONG PRODUCTION: SEARCH FOR SUSY IN FINAL STATES WITH JETS AND MISSING TRANSVERSE MOMENTUM WITH THE ATLAS DETECTOR

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MANFREDI RONZANI

ADVISOR: PROF. DR. GREGOR HERTEN



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|                      |                             |
|----------------------|-----------------------------|
| DEKAN:               | Prof. Dr. Gregor Herten     |
| BETREUER DER ARBEIT: | Prof. Dr. Gregor Herten     |
| KOREFERENT:          | Prof. Dr. Markus Schumacher |
| PRÜFER:              | Prof. Dr. Gregor Herten     |
|                      | Prof. Dr. Harald Ita        |
|                      | Dr. Christian Weiser        |



*Ad Ada, amore e vita mia.*

*The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'*

— Isaac Asimov

## ABSTRACT

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If SUSY is present at the TeV scale, the pair production of the supersymmetric partners of the quarks and the gluons is among the most favoured to be generated at the LHC. This work describes a search for squarks and gluinos in final states containing jets and missing transverse momentum, but no leptons, performed using  $36.1 \text{ fb}^{-1}$  of proton-proton collision data recorded by the ATLAS detector at  $\sqrt{s} = 13 \text{ TeV}$ . No significant deviations between data and the Standard Model expectations have been found. Therefore, the analysis results are interpreted using various supersymmetric models. For previously investigated SUSY models, the exclusion limits were significantly improved. In addition, several other new models were investigated.

A dedicated study on the improvement of the analysis sensitivity is performed as original contribution in scenarios where heavy gauge bosons coming from sparticles decays gain sufficient transverse momentum to be reconstructed as single jets. Jet reclustering techniques for the boson reconstruction are studied and implemented in the analysis. Other contributions to the analysis concerning the SUSY signals and their uncertainties are also included.

## ZUSAMMENFASSUNG

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Wenn Supersymmetrie auf TeV-Skalen existiert, gehört die Erzeugung der supersymmetrischen Partner von Quarks und Gluonen zu den bevorzugten Produktionsmechanismen am LHC. Diese Arbeit behandelt eine Suche nach diesen Teilchen in Ereignissen ohne Leptonen, aber mit Jets und fehlender transversaler Energie. Für die Suche werden Daten des ATLAS Detektors aus Proton-Proton Kollisionen verwendet, welche bei einer Schwerpunktsenergie von 13 TeV aufgezeichnet wurden. Der Datensatz umfasst  $36.1 \text{ fb}^{-1}$ . Es wurden keine signifikanten Abweichungen von der Vorhersage des Standardmodells gefunden. Die Resultate der Analyse wurden daher im Rahmen verschiedener vereinfachter supersymmetrischer Modelle interpretiert, die teilweise bereits in vorherigen Suchen Anwendung fanden.

Eine spezielle Sensitivitätsstudie wurde als Originalbeitrag durchgeführt, die davon ausgeht, dass die schweren Eichbosonen, die beim Zerfall supersymmetrischer Teilchen erzeugt werden, durch ihren großen Transveralimpuls als einzelne Jets rekonstruiert werden.

Jet-Rekombinationsalgorithmen (jet-reclustering) wurden für die Bosonenrekonstruktion untersucht und in die Analyse implementiert. Weitere Studien im Rahmen der Analyse bezüglich der SUSY-Signale und deren Unsicherheiten wurden in dieser Arbeit ebenfalls behandelt.

## PUBLICATIONS

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The material presented in this thesis is based on work performed within the ATLAS collaboration, thus relying on the contribution of many people. The author's personal contribution is here briefly summarised.

SEARCHES FOR SQUARKS AND GLUINOS IN FINAL STATES WITH JETS AND MISSING TRANSVERSE MOMENTUM USING 36 FB-1 OF 13 TEV PP COLLISION DATA WITH THE ATLAS DETECTOR [1]

The author has been responsible for introducing and developing the Boosted Analysis using the jet reclustering technique within the SUSY 0-lepton analysis; for studying the modeling and the theory uncertainties of the SUSY signal samples; for introducing and setting the exclusion limits on new SUSY signal models considering the presence of multiple bosons (W/Z/h) in final state. For general analysis work and software development.

LIMITS ON METASTABLE GLUINOS FROM ATLAS SUSY SEARCHES AT 8 TEV [2]

The author introduced the new signal model with metastable gluinos in the SUSY 0-lepton analysis, studied and requested the signal Monte Carlo production and performed an interpretation using the 0-lepton analysis signal regions defined in [3], providing signal efficiency studies and limit calculation.

SEARCH FOR SQUARKS AND GLUINOS WITH THE ATLAS DETECTOR IN FINAL STATES WITH JETS AND MISSING TRANSVERSE MOMENTUM USING 8 TEV PROTON-PROTON COLLISION DATA [3]

The author performed a study on a method for the multijet background estimate.



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---

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# CONTENTS

---

|                                                         |           |
|---------------------------------------------------------|-----------|
| INTRODUCTION                                            | 1         |
| <b>i THEORY</b>                                         | <b>3</b>  |
| 1 THE STANDARD MODEL                                    | 5         |
| 1.1 Introduction                                        | 5         |
| 1.2 Particle Content and Interactions                   | 6         |
| 1.2.1 Fermions                                          | 6         |
| 1.2.2 Bosons                                            | 6         |
| 1.3 The Electroweak Sector                              | 8         |
| 1.3.1 Quantum Electrodynamics                           | 8         |
| 1.3.2 Electroweak Interaction                           | 8         |
| 1.3.3 Spontaneous Symmetry Breaking and the Higgs Boson | 11        |
| 1.3.4 Fermion Masses and Mixing                         | 13        |
| 1.4 The Strong Sector                                   | 14        |
| 1.4.1 Quantum Chromodynamics                            | 14        |
| 1.4.2 Renormalization                                   | 15        |
| 1.4.3 Color Confinement                                 | 15        |
| 1.5 Summary of the Standard Model                       | 16        |
| 1.6 Shortcomings of the Standard Model                  | 17        |
| 1.6.1 Dark Matter                                       | 18        |
| 1.6.2 Gauge Coupling Unification                        | 18        |
| 1.6.3 Hierarchy Problem                                 | 19        |
| 2 SUPERSYMMETRY                                         | 21        |
| 2.1 Introduction                                        | 21        |
| 2.2 Supersymmetry Algebra                               | 21        |
| 2.3 The Minimal Supersymmetric Standard Model           | 22        |
| 2.3.1 Particle Content of the MSSM                      | 22        |
| 2.3.2 Solution to the SM shortcomings                   | 24        |
| 2.4 SUSY Breaking                                       | 24        |
| 2.4.1 R-parity                                          | 26        |
| 2.4.2 Higgs sector in the MSSM                          | 27        |
| 2.4.3 Mass spectrum                                     | 28        |
| 2.5 SUSY Phenomenology                                  | 29        |
| 2.5.1 The Phenomenological MSSM                         | 30        |
| 2.5.2 Simplified Models                                 | 30        |
| 2.6 Experimental Constraints on SUSY                    | 31        |
| <b>ii EXPERIMENT</b>                                    | <b>35</b> |
| 3 LHC AND ATLAS                                         | 37        |
| 3.1 CERN and the Large Hadron Collider                  | 37        |
| 3.1.1 Experiments at the LHC                            | 37        |
| 3.1.2 The Accelerator Complex and Design                | 38        |
| 3.1.3 LHC Design and Luminosity                         | 39        |
| 3.1.4 LHC Performancies                                 | 40        |

|       |                                                       |     |
|-------|-------------------------------------------------------|-----|
| 3.2   | The ATLAS experiment                                  | 41  |
| 3.2.1 | Detector Layout                                       | 44  |
| 3.2.2 | Magnet System                                         | 44  |
| 3.2.3 | Inner Detector                                        | 46  |
| 3.2.4 | Calorimeters                                          | 49  |
| 3.2.5 | Muon Spectrometer                                     | 53  |
| 3.2.6 | Forward Detectors                                     | 55  |
| 3.2.7 | Trigger and Data Acquisition                          | 56  |
| 3.2.8 | Data Quality and Performances of the ATLAS Experiment | 59  |
| 4     | MONTE CARLO SIMULATION SAMPLES                        | 63  |
| 4.1   | Simulation of pp Collisions                           | 63  |
| 4.1.1 | Factorisation Theorem                                 | 63  |
| 4.1.2 | Parton Distribution Function                          | 65  |
| 4.1.3 | Hard Scattering: Matrix Elements                      | 66  |
| 4.1.4 | Parton Showers                                        | 67  |
| 4.1.5 | Matrix Element and Parton Shower Matching             | 68  |
| 4.1.6 | Underlying Events                                     | 68  |
| 4.1.7 | Hadronisation                                         | 69  |
| 4.2   | Monte Carlo Generators                                | 70  |
| 4.2.1 | General Purpose MC Generators                         | 70  |
| 4.2.2 | Matrix Element Generators                             | 70  |
| 4.3   | ATLAS Detector Simulation                             | 71  |
| 5     | OBJECT RECONSTRUCTION AND PARTICLE IDENTIFICATION     | 73  |
| 5.1   | Tracking and vertexing                                | 73  |
| 5.1.1 | Track Reconstruction                                  | 73  |
| 5.1.2 | Vertex Reconstruction                                 | 75  |
| 5.2   | Jets                                                  | 77  |
| 5.2.1 | Topological Clustering                                | 77  |
| 5.2.2 | Jets Reconstruction and Calibration                   | 78  |
| 5.2.3 | Jet Energy Scale and Resolution Uncertainties         | 82  |
| 5.3   | Jet Reclustering Algorithm                            | 82  |
| 5.4   | Bottom Quark Tagging                                  | 84  |
| 5.4.1 | Boosted Decision Tree Algorithm <i>MV2</i>            | 85  |
| 5.5   | Electrons and Photons                                 | 85  |
| 5.5.1 | Electrons                                             | 86  |
| 5.5.2 | Photons                                               | 89  |
| 5.6   | Muons                                                 | 91  |
| 5.7   | Missing Transverse Momentum                           | 94  |
| 5.8   | Overlap Removal                                       | 97  |
| iii   | ANALYSIS                                              | 99  |
| 6     | ANALYSIS INTRODUCTION                                 | 101 |
| 6.1   | Analysis Strategy                                     | 101 |
| 6.2   | Signal Regions                                        | 102 |
| 6.3   | Discriminating Variables                              | 103 |
| 6.4   | Optimisation Methods                                  | 104 |
| 6.4.1 | Best Discovery                                        | 104 |

|        |                                                                   |     |
|--------|-------------------------------------------------------------------|-----|
| 6.4.2  | Best Exclusion                                                    | 106 |
| 6.5    | Control Regions                                                   | 106 |
| 6.5.1  | Validation Regions                                                | 107 |
| 6.6    | Statistical Procedure                                             | 108 |
| 6.6.1  | The Likelihood Function                                           | 108 |
| 6.6.2  | Analysis Fits                                                     | 109 |
| 6.6.3  | Profile Log-Logarithmic Ratio                                     | 110 |
| 7      | SUSY WITH NO LEPTONS                                              | 113 |
| 7.1    | SUSY Models                                                       | 114 |
| 7.1.1  | Simplified Models with Direct or One-Step Decays                  | 114 |
| 7.1.2  | Simplified Models with W/Z/h Bosons in Final State                | 115 |
| 7.1.3  | pMSSM                                                             | 116 |
| 7.2    | Standard Model Backgrounds                                        | 116 |
| 7.2.1  | Top                                                               | 116 |
| 7.2.2  | Vector Boson + Jets                                               | 117 |
| 7.2.3  | Diboson                                                           | 117 |
| 7.2.4  | Multijets                                                         | 117 |
| 7.3    | Monte Carlo Samples                                               | 118 |
| 7.3.1  | Signal Samples                                                    | 118 |
| 7.3.2  | Background Samples                                                | 118 |
| 7.3.3  | Pile-up Reweighting                                               | 119 |
| 7.4    | Dataset and Trigger                                               | 120 |
| 7.4.1  | Dataset                                                           | 120 |
| 7.4.2  | Trigger                                                           | 120 |
| 7.5    | Object Definition                                                 | 122 |
| 7.6    | Event Preselection                                                | 123 |
| 7.6.1  | Event Cleaning                                                    | 123 |
| 7.6.2  | Preselection                                                      | 125 |
| 7.7    | Event Selection                                                   | 126 |
| 7.8    | Boosted Analysis                                                  | 128 |
| 7.8.1  | Optimisation for Discovery with $13.3 \text{ fb}^{-1}$ of pp Data | 128 |
| 7.8.2  | Optimisation for Exclusion with $36.5 \text{ fb}^{-1}$ of pp Data | 130 |
| 7.9    | Background estimation                                             | 139 |
| 7.9.1  | Control Regions                                                   | 139 |
| 7.9.2  | Validation Regions                                                | 141 |
| 7.9.3  | Fake Lepton Background                                            | 144 |
| 7.9.4  | QCD Multijet Background Estimation                                | 144 |
| 7.9.5  | Pre-fit Control Region Distributions                              | 145 |
| 7.9.6  | Control Region Selection for Boosted Analysis                     | 150 |
| 7.10   | Systematic uncertainties                                          | 153 |
| 7.10.1 | Uncertainties on Background                                       | 153 |
| 7.10.2 | Uncertainties on Signal                                           | 156 |
| 7.10.3 | Signal Cross Section Uncertainty                                  | 156 |
| 7.11   | Signal Theory Uncertainties                                       | 157 |
| 7.12   | Systematic Uncertainties in Boosted Analysis                      | 158 |

|        |                                                                |     |
|--------|----------------------------------------------------------------|-----|
| 7.12.1 | Jet Mass Scale                                                 | 158 |
| 7.12.2 | Jet Mass Resolution                                            | 160 |
| 7.13   | Fit results                                                    | 161 |
| 7.13.1 | Background-only Fit Results                                    | 162 |
| 7.13.2 | Results in Validation Regions                                  | 163 |
| 7.13.3 | Results in Signal Regions                                      | 163 |
| 7.13.4 | Impact of the Systematic Uncertainties                         | 164 |
| 7.13.5 | Boosted Analysis Results                                       | 166 |
| 8      | INTERPRETATION                                                 | 173 |
| 8.1    | Updated Limits on Simplified Models                            | 173 |
| 8.1.1  | Direct Decays                                                  | 173 |
| 8.1.2  | One-step Decays                                                | 173 |
| 8.2    | Limits set with Boosted Analysis                               | 176 |
| 8.3    | Limits on new Models for 0-lepton Analysis                     | 176 |
| 8.4    | Limits on Phenomenological MSSM Model                          | 179 |
| 9      | CONCLUSIONS                                                    | 183 |
| 9.1    | Analysis Summary                                               | 183 |
| 9.2    | Discussion                                                     | 183 |
| 9.3    | Outlook                                                        | 185 |
| iv     | APPENDIX                                                       | 187 |
| A      | CONTROL REGION PLOTS FOR BOOSTED ANALYSIS                      | 189 |
| A.1    | Control Region Plots for 2jB-1600                              | 189 |
| A.2    | Control Region Plots for 2jB-2400                              | 199 |
| B      | MULTIJET BACKGROUND ESTIMATION BASED ON $E_{T,track}^{miss}$   | 209 |
| B.1    | Introduction                                                   | 209 |
| B.2    | The ABCD Method                                                | 210 |
| B.3    | Results and Conclusion                                         | 211 |
| C      | LIMITS ON METASTABLE GLUINOS FROM ATLAS SUSY SEARCHES AT 8 TEV | 213 |
| C.1    | Motivation and Models                                          | 213 |
| C.2    | Simulated Samples                                              | 213 |
| C.3    | Analysis and Results                                           | 214 |
| C.4    | Discussion and Conclusion                                      | 215 |
| v      | OTHER                                                          | 219 |
|        | BIBLIOGRAPHY                                                   | 221 |

## INTRODUCTION

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The start of the Large Hadron Collider (LHC) has been a game changer in the history of the research in elementary particle physics at the TeV scale. It enabled the observation of the long searched Higgs boson and furthermore provides incredibly precise measurements on the properties of already known particles. The data recorded by the various detectors present at the LHC allow to explore the possibilities of physics beyond the Standard Model, as the one supplied by Supersymmetry (SUSY).

The Standard Model of particle physics, introduced in Chapter 1, has shown to be a successful and predictive theory by many experimental results since its initial formulation, in the 1960's. The agreements with the SM predictions followed one another over the last decades, from the discovery of its predicted particles to the measurements of their properties. The hunt for the last missing brick of such an successful theory, the Higgs boson, was one of the main goals for building the LHC, which is the most powerful hadron collider ever constructed, along with its multipurpose detectors ATLAS and CMS. The quest successfully ended in 2012, when the Higgs boson was finally observed.

However, the current formulation of the SM leaves several fundamental questions uncovered, either brought up by experimental observations or coming from theoretical arguments. Moreover, not all the physical effects known in the Universe are explained by the SM, which for examples lacks of a formulation for gravity and does not include any particle candidate for dark matter.

Supersymmetry is one of the most promising attempts to deal with the open questions of the SM. An overview of the SUSY theory is given in Chapter 2. SUSY postulates an extension of the Poincaré group to include a symmetry between fermions and bosons. Doing so, SUSY provides elegant mathematical solutions to several SM issues and a good candidate for dark matter, while protecting the Higgs boson mass against radiative corrections growing quadratically with the energy scale. In addition, the particles predicted by SUSY may be produced as the outcome of high-energy  $pp$  collisions, making it a testable theory at the LHC.

The experimental setup used to produce and detect heavy particles, notably the Large Hadron Collider operated by the European Organisation for Nuclear Research (CERN) and the ATLAS experiment, are described in Chapter 3. After the detection, each recorded event is reconstructed algorithmically from the footprints left as a result of its interaction with the detector, allowing a particle identification via the procedure reviewed in Chapter 5. In order to test the validity of the investigated theory, the obtained dataset must be compared with the

expected results, whose physics processes and interaction with the detector are fully simulated via different Monte Carlo (MC) techniques, reviewed in Chapter 4.

The search for supersymmetric partners of the SM particles can be performed in many different signatures, depending on the ways SUSY may manifest itself. The analysis presented in this work ("0-lepton") looks for events with jets and missing transverse momentum ( $E_T^{\text{miss}}$ ) in the final state, which constitute a favorable dataset as the  $E_T^{\text{miss}}$  can be associated with the presence of the lightest SUSY particle while events with jets are the most predominant outcome of the collisions at the LHC. An introduction to the analysis structure and the statistical methods employed is given in Chapter 6. A complete description of the analysis performed with  $36.1 \text{ fb}^{-1}$  of  $\text{pp}$  collision data at  $\sqrt{s} = 13 \text{ TeV}$  is provided in Chapter 7. The author's contributions include studies on the SUSY signals and their uncertainties and on the sensitivity to SUSY models not previously investigated. In addition, a study on the design and the implementation of two signal regions has been performed targeting the improvement of the analysis sensitivity in scenarios where boosted  $W, Z$  bosons appear in the cascade decays of primary produced SUSY particles. Hadronically decaying boson resonances can be here reconstructed as single jets in the final state by using jet-reclustering techniques, which allows a re-definition of the jet cone-size without dramatically increasing the systematic uncertainties. The mass of the reclustered jets is then used for boson tagging.

Since no significant excess over the SM expectations have been observed, the results are used to set limits on the visible production cross section of physics beyond Standard Model (BSM) and specifically to set model-dependent limits in the SUSY parameter-space. All the interpretation results set by the 0-lepton analysis are discussed in Chapter 8. Generally, the limits extend substantially beyond previously obtained results or set new limits on not previously investigated models. A specific section is dedicated to the contribution given by the boosted analysis on the SUSY parametric space exclusion reach.

Finally, Chapter 9 ends this work with some conclusive remarks on the search for Supersymmetry in the 0-lepton channel and discusses more broadly the current status of the search for SUSY after the 2015-2016 Run2 data taking period.

Two additional contributions regarding studies performed on the dataset recorded by ATLAS at  $\sqrt{s} = 8 \text{ TeV}$  are included in the appendices of this thesis. The first study concerns a multijet background estimation with a data-driven method (Appendix B). The second contribution shows a re-interpretation of the results of the analysis performed at  $\sqrt{s} = 8 \text{ TeV}$  in the context of a SUSY model with metastable gluinos (Appendix C).

Part I

THEORY





## THE STANDARD MODEL

---

Our present scientific understanding of the smallest constituents of the Universe, the elementary particles, is based on the Standard Model (SM) of particle physics, a theoretical framework developed through decades in the XX century. The SM provides an overall description of all the known fundamental particles and their interactions, with the exception of the gravity. The success of the SM relies on the outstanding experimental and theoretical achievements at all energy scales explored so far over the past sixty years. It is currently the most precisely tested physical theory. Nevertheless, the SM cannot be considered as the ultimate theory of particle physics, given several limitations shown by a number of experimental observations and theoretical arguments. The formulation of a more complete theory for higher energies, which holds the SM as a low energy approximation, is then foreseen.

This chapter gives a brief review of the Standard Model and shows its shortcomings.

### 1.1 INTRODUCTION

The Standard Model is a renormalizable quantum field theory (QFT) in which each particle is described by a field in space-time and all the interactions between the particles are described by Yang-Mills theories [4], based on the overarching gauge symmetry group  $SU(3)_C \times SU(2)_L \times U(1)_Y$ <sup>1</sup>. Each force is mediated by a single or several gauge bosons.

The Standard Model describes three out of the four fundamental interactions: the electromagnetic (EM), weak and strong forces. The gauge theory of the strong interaction is called quantum chromodynamics (QCD) [5, 6]. The EM and weak interactions are unified in a unique *electroweak* theory with a single characteristic energy scale. The unified description is based on a spontaneously broken gauge symmetry firstly formulated by Glashow [7] and later completed by Weinberg [8] and Salam [9] via the incorporation of the concept of the mass generation through symmetry breaking of a local gauge symmetry. The concept was independently developed by Higgs [10] and Brout, Englert [11] and the phenomenon, universally known as the *Higgs mechanism*, provides the natural framework for the electroweak unification.

The SM does not include the gravitational force in its description, since no consistent quantum gravity theory currently exists. However, the coupling strength of the gravitational interaction is extremely weak and its contribution would be in any case negligible in high energy physics scale.

---

<sup>1</sup> The subscript C is for the color charge, L for the left-handed weak charge and Y for the hypercharge.

## 1.2 PARTICLE CONTENT AND INTERACTIONS

1.2.1 *Fermions*

The constituents of the matter included in the SM description are 12 fundamental particles of spin 1/2 called *fermions*, which can be represented as Dirac spinors. The SM is formulated in terms of *Lagrangian* densities describing particle fields and their interactions. A Lagrangian for a free fermion with mass  $m$  is written as:

$$\mathcal{L}_{\text{Dirac}} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (1)$$

where  $\gamma^\mu$ , ( $\mu = 0, 1, 2, 3$ ) are the Dirac matrices and  $\bar{\psi}$  is the adjoint of the Dirac spinor ( $\bar{\psi} = \psi^\dagger\gamma^0$ ).

The fermions are further classified in two categories: *leptons* and *quarks*. The difference is due to the type of *quantum numbers* each fermion carries. Charged particles are subject to the EM force, while quarks have a colour charge causing them to interact also strongly. All the fermions have weak *isospin*, so that they undergo weak interaction. Consequently, leptons experience only weak and EM interactions, while quarks experience also strong interaction. For each fermion, a corresponding anti-particle, with conjugated additive quantum number exists.

Fermions are organised in three generations (or *families*), copies of the first one with increasing mass but with same quantum numbers. A fourth generation is theoretically possible but has never been observed and is disfavoured by several experimental results [12]. The 1<sup>st</sup> family consists of the charged electron ( $e$ ) and the electrically neutral electron-neutrino ( $\nu_e$ ) for the lepton side, and of the up ( $u$ ) and down ( $d$ ) quarks. The latter build up the proton ( $p$ ) and the neutron ( $n$ ). Therefore, the first generation accounts for the stable, visible matter in the Universe. Particles from the second and third generations are unstable and decay.

In the quark sector, each generation is build by a quark with electric charge  $2/3e$  and an other quark with electric charge  $-1/3e$ . Quarks can be arranged by strong interaction in bound states, called hadrons, of  $q\bar{q}$  pairs (*mesons*) or three quarks (*baryons*). As it is forbidden to have fermions in the same state, due to Pauli's principle, quarks must have a new quantum number called *color*, which comes in three different types. A summary of all this particle categorization can be found in Table 1.

1.2.2 *Bosons*

The interactions included in the SM are mediated by the exchange of spin 1 particles, called *gauge bosons*. Those particles are needed in order to maintain local invariance of the Lagrangian density function of the physical system. In fact, local gauge transformations of the free Lagrangian density produce the need to introduce gauge fields (i.e. the gauge bosons) to preserve local-gauge invariance. The invariance can be seen as a *symmetry* of the function. According to Noether's theorem [14],

| Family          | Leptons    | Q[e] | Mass[GeV]              | Quarks | Q[e] | Mass[GeV]                 |
|-----------------|------------|------|------------------------|--------|------|---------------------------|
| 1 <sup>st</sup> | e          | -1   | $0.511 \cdot 10^{-3}$  | u      | 2/3  | $\sim 2.49 \cdot 10^{-3}$ |
|                 | $\nu_e$    | 0    | $< 2 \cdot 10^{-9}$    | d      | -1/3 | $\sim 5.05 \cdot 10^{-3}$ |
| 2 <sup>nd</sup> | $\mu$      | -1   | 0.106                  | c      | 2/3  | $\sim 1.27$               |
|                 | $\nu_\mu$  | 0    | $< 0.19 \cdot 10^{-3}$ | s      | -1/3 | $\sim 0.10$               |
| 3 <sup>rd</sup> | $\tau$     | -1   | 1.777                  | t      | 2/3  | $\sim 172$                |
|                 | $\nu_\tau$ | 0    | $< 18.2 \cdot 10^{-3}$ | b      | -1/3 | $\sim 4.19$               |

Table 1: Fermion fields in the SM and their electric charge and mass. The numbers are taken from [13].

when a symmetry is introduced in the system, a conserved current  $J^\mu(x)$  must exist verifying the continuity equation:

$$\partial_\mu J^\mu = 0 \quad (2)$$

Eq. (2) implies that the integral over a large space of the time-component  $J^0$  must remain constant, i.e. conservation of a charge. Therefore, each interaction force has to conserve a quantum number.

The massless *photon*  $\gamma$  is the carrier of the electromagnetic interaction, coupling to the electrically charged particles. The weak interaction is transmitted by the massive  $W^\pm$  and  $Z$  bosons, with masses of  $m_W = 80.4$  GeV and  $m_Z = 91.2$  GeV, respectively. Their heavy masses limit the range of the weak interaction and make the coupling be weak at low energy. The strong interaction is mediated by eight neutral massless *gluons*  $g$ , which couple to colour charge.

In order for the  $W, Z$  boson to be massive, a neutral scalar particle is introduced in the SM: the Higgs boson (H). Depending on the mass of the massive particle, the coupling with the H varies.

A summary of the interaction mediators and their properties can be found in the Table 2.

| Interaction | Particle | Q[e]    | Spin | Mass[GeV] |
|-------------|----------|---------|------|-----------|
| EM          | $\gamma$ | 0       | 1    | 0         |
| Weak        | $W^\pm$  | $\pm 1$ | 1    | 80.4      |
|             | $Z$      | 0       | 1    | 91.2      |
| Strong      | $g$      | 0       | 1    | 0         |
|             | H        | 0       | 0    | 125.09    |

Table 2: Interactions of the SM and their mediating gauge bosons fields in the SM and their properties. The numbers are taken from [13].

### 1.3 THE ELECTROWEAK SECTOR

#### 1.3.1 *Quantum Electrodynamics*

The quantum electrodynamics (QED) is the result of the combination between the classical theory of EM interaction and a consistent relativistic and quantistic description of electrons. The QED is based on the gauge invariance of electrodynamics, which is introduced demanding the Lagrangian in Eq. (1) of a free fermion to be invariant under the local gauge transformation, belonging to the  $U(1)$  group:

$$\psi \rightarrow \psi' = e^{i\alpha(x)}\psi = e^{-ie\lambda(x)}\psi \quad (3)$$

The Dirac Lagrangian has to be consistently modified through the minimal substitution of the derivative with a covariant derivative of the following form:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ieA_\mu \quad (4)$$

achieving a theory which couples Dirac fermions and the vectorial field  $A_\mu$ , which transforms as:

$$A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \lambda(x) \quad (5)$$

Adding a kinetic term  $\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$  to the Lagrangian of Eq. (1) leads to the Maxwell equations. The Lagrangian transforms as:

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \quad (6)$$

Eq. (6) describes a Dirac field, representing a fermion, and a vectorial field, interpretable as a photon, mutually interacting with a coupling proportional to the electric charge  $e$ . We can form the electron current  $J^\mu = -e\bar{\psi}\gamma^\mu\psi$  out of the Dirac field. Since  $\psi$  satisfies the Dirac equation,  $J^\mu$  is conserved, so that  $J^\mu$  is a Noether current associated with the conserved quantity of the  $U(1)$  symmetry, which is therefore the electric charge  $e$ .

The illustrated procedure provides a consistent way to construct gauge theories. Once the gauge group is chosen, the interaction structure is consequently fixed. Additional fermions can be added to the theory by simply including the corresponding interaction and kinetic terms for each of them to the QED Lagrangian. Finally, since a mass term for the vectorial field of the form  $\frac{1}{2}mA_\mu A^\mu$  is not locally gauge invariant under  $U(1)$  transformations, the vectorial field  $A_\mu$  (i.e. the photon  $\gamma$ ) is required to be massless.

#### 1.3.2 *Electroweak Interaction*

The first theory for weak processes was proposed by E.Fermi in 1934 [15]. In order to explain the  $\beta$ -decay  $n \rightarrow p e \bar{\nu}_e$ , he introduced a four-fermion interaction vertex with a current-current amplitude of the form:

$$\mathcal{M} = G_F (\bar{u}_p \gamma^\mu u_n) (\bar{u}_e \gamma_\mu u_{\nu_e}) \quad (7)$$

where  $\mathbf{u}_p$  and  $\mathbf{u}_n$  are the Dirac spinors of the proton and the neutron, respectively, while  $\mathbf{u}_e$  and  $\mathbf{u}_{\nu_e}$  are the Dirac spinors of electron and the neutrino, and  $G_F = 1.166 \cdot 10^{-5} \text{ GeV}^{-2}$  is the Fermi coupling constant.

Later in 1957, S. Wu's experiment [16] showed parity violation of  $^{60}\text{Co}$  decay in  $^{60}\text{Ni}$ , not explained by Fermi's theory.

A new form of interaction was suggested by replacing  $\gamma^\mu$  with  $\gamma^\mu(1 - \gamma^5)$  in Eq. (7), where  $\gamma^5$  is defined by using the chiral representation as:

$$\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \end{pmatrix} \quad (\gamma^5)^2 = 1 \quad \{\gamma^5, \gamma^\mu\} = 0 \quad (8)$$

with which we may form the Lorentz invariant projection operators  $P_\pm = \frac{1}{2}(1 \pm \gamma^5)$  differentiating the chirality of a Dirac spinor  $\psi$ :

$$\psi_L = \frac{1}{2}(1 - \gamma^5)\psi, \quad \psi_R = \frac{1}{2}(1 + \gamma^5)\psi \quad (9)$$

We can now describe the interaction between fermions and bosons corresponding to the exchange of a spin-1 particle in the most general form as a linear combination of *vector* current  $J_V^\mu = \bar{\psi}\gamma^\mu\phi$  and *axial-vector* current  $J_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\phi$ , the so-called V-A structure.

To respect the structure, we introduce  $SU(2)_L$  symmetry where left-handed fermions transform as isodoublets, while right-handed fermions transform as singlets:

$$\text{leptons} : l_L = \begin{pmatrix} \nu_L^i \\ l_L^i \end{pmatrix}, l_R^i \quad (10)$$

$$\text{quarks} : Q_L = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, u_R^i, d_R^i \quad (11)$$

where  $i = 1, 2, 3$  is the family index. The  $SU(2)_L$  group generators are the weak isospin operators  $\hat{T}_i = \sigma_i/2$  and a new quantum number, referred as *weak isospin*  $T_3$  is introduced. The two components of the doublet  $\psi_L$  have  $T_3 = 1/2$ , while  $\psi_R$  singlet has  $T_3 = 0$  and therefore does not interact under  $SU(2)_L$ .

The formulation of a unified electroweak theory relies on a single underlying gauge group  $SU(2)_L \times U(1)_Y$ , also known as the Glashow-Weinberg-Salam (GSM) model, where  $Y$  denotes the *hypercharge*. Differently from the QED case, the conserved charge related to the  $U(1)$  symmetry is the hypercharge, which is related to the electric charge  $Q$  and the weak isospin  $T_3$  via the Gell-Mann-Nishijima formula:

$$Q = T_3 + \frac{Y}{2} \quad (12)$$

an expression that also ensures a proper normalization to the weak hypercharge, that would otherwise remain arbitrary.

The gauge fields corresponding to the  $SU(2)_L \times U(1)_Y$  symmetry are three  $SU(2)$  bosons  $\bar{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$  and one  $U(1)$  boson  $B_\mu$ . In order to respect the local invariance under both symmetry groups, the covariant derivative is here modified as:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ig\bar{\sigma} \cdot \bar{W}_\mu + ig'\frac{Y}{2}B_\mu \quad (13)$$

with  $g$  and  $g'$  are the interaction strengths of the  $SU(2)$  and  $U(1)$  interactions. The Lagrangian term representing the coupling to the fermion sector can be schematically written as:

$$\mathcal{L}_f = i\bar{\psi}_L \not{D}\psi_L + i\bar{\psi}_{l_R} \not{D}\psi_{l_R} + i\bar{\psi}_{Q_L} \not{D}\psi_{Q_L} + i\bar{\psi}_{u_R} \not{D}\psi_{u_R} + i\bar{\psi}_{d_R} \not{D}\psi_{d_R} \quad (14)$$

where  $\psi_L$  and  $\psi_{l_R}$  are, respectively, the  $SU(2)$  left-handed doublets and right-handed singlet from Eq. (10) (with implicit sum over the three lepton flavours  $e, \mu, \tau$ ), while  $\psi_{Q_L}$  and  $\psi_{u_R, d_R}$  are the  $SU(2)$  left-handed quark doublets and  $SU(2)$  right-handed quark singlet, for the  $u, d$  quark types, respectively, from Eq. (11).

The overall unified electroweak Lagrangian can be then written as:

$$\mathcal{L}_{EW} = \mathcal{L}_f - \frac{1}{4}\bar{W}^{\mu\nu} \cdot \bar{W}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \quad (15)$$

The interaction terms of the four gauge bosons given in the second part of  $\mathcal{L}_{EW}$  are given by:

$$\begin{aligned} W_{\mu\nu}^a &= \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - 2g\epsilon^{abc}W_\mu^b \cdot W_\nu^c \\ B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \end{aligned} \quad (16)$$

Finally, the physical fields  $W_\mu^\pm, Z_\mu, A_\mu$  representing the weak and EM gauge bosons, i.e.  $W^\pm, Z, \gamma$ , are obtained by mixing the already introduced gauge fields:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2) \\ A_\mu &= B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \\ Z_\mu &= -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \end{aligned} \quad (17)$$

where  $\theta_W$  is the Weinberg angle which relates to the EM and weak coupling constant as:

$$e = g\cos\theta_W = g'\sin\theta_W \quad (18)$$

The  $Z$  has a  $B$  component causing its coupling also to right-handed fermions, while the  $W$  only mediates purely left-handed interactions. The coupling between the fermions and the  $Z$  boson occurs only within the same family, as Flavor-Changing-Neutral-Currents (FCNC) are not allowed in the SM at tree level. The flavour sector of SM has been tested in many experiment and very stringent constraints hold.

In the theory exposed so far, mass terms for vector bosons are not included, as mass terms bilinear in the fields ( $\sim A_\mu A^\mu$ ) violate gauge invariance as in the QED case. Moreover, the EW model also forbids fermion mass terms of the form  $m\bar{\psi}\psi = m\bar{\psi}_R\psi_L + m\bar{\psi}_L\psi_R$ , which violates the gauge invariance due to the different transformation properties of left- and right-handed fermions, as well as it makes the theory non-renormalizable. The experimental observations of massive vector bosons requires a mechanism for generating non-zero masses, while preserving the renormalizability of the theory.

### 1.3.3 Spontaneous Symmetry Breaking and the Higgs Boson

In the electroweak theory the mass of the vector bosons arises from spontaneous symmetry breaking (SSB) of the  $SU(2)_L \times U(1)_Y$  gauge symmetry caused by the arbitrary selection of non-unique ground state (i.e. the *vacuum*). The procedure starts considering a new scalar  $SU(2)_L$  isospin doublet of hypercharge  $Y = 1$ :

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (19)$$

where the electric charge of the field is specified by "+" and "0". The corresponding Lagrangian is:

$$\mathcal{L}_\Phi = T - V = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \quad (20)$$

where  $D_\mu$  has been already defined in Eq. (13) and  $V(\Phi)$  is the most general renormalizable potential including self-interactions:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (21)$$

The potential  $V(\Phi)$  depends on two parameters:  $\mu^2$  and  $\lambda$ . The case  $\lambda < 0$  is unphysical and would lead to non-stable minimum. In case of  $\lambda > 0$ ,  $\mu^2$  can be chosen to describe two different scenarios, as represented in Figure 1. For  $\mu^2 > 0$ , there is a single trivial solution at  $|\Phi| = 0$ , with no symmetry breaking. For  $\mu^2 < 0$ , the potential has an unstable maxima at the origin and an infinity of degenerate non-zero vacuum states in a circle defined by:

$$\Phi^\dagger \Phi = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} \quad (22)$$

where  $\Phi_0 \equiv \langle 0|\Phi|0\rangle = v/\sqrt{2}$  is the field vacuum expectation value (vev). Since there is no unique minimum, the fundamental vacuum state is not gauge invariant under  $SU(2)_L \times U(1)_Y$  and the two symmetries are therefore broken.

According to Goldstone theorem [17], whenever a continuous symmetry is broken a massless scalar boson occurs. Using Eq. (22) in the ground state, the  $\phi^+$  component vanishes as the vacuum should be electrically neutral so that  $\Phi_0$  is fixed up to an arbitrary phase. In addition, parametrizing the field around the vev, the scalar field  $\Phi$  becomes:

$$\Phi = U(x) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (23)$$

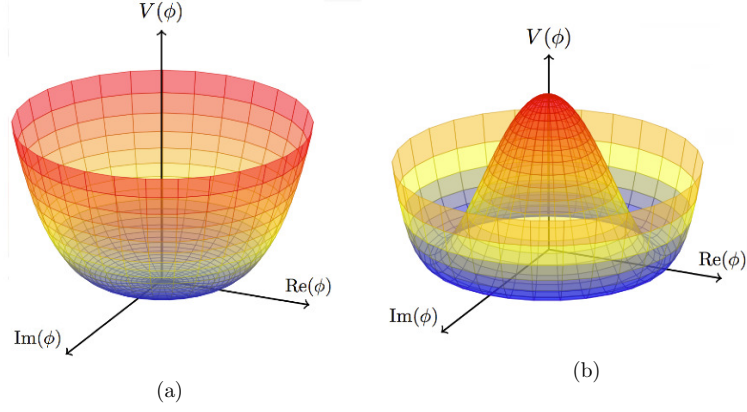


Figure 1: Representation of the Higgs vacuum potential for the case  $\lambda > 0$  and  $\mu^2 > 0$  (a) or  $\mu^2 < 0$  (b), where the equivalent minima are connected in the  $(\text{Im}(\phi), \text{Re}(\phi))$  plane).

The two-component spinor has an arbitrary real-valued lower component, given by the vev  $v$  plus a real-valued field  $H(x)$  fluctuating around the vacuum in the perpendicular direction of the degenerate minima. We can choose a gauge transformation, called *Unitarity gauge*, that absorbs  $U(x)$  and makes the spectrum obvious with no Goldstone bosons, reducing  $\phi$  to a field with only 1 degree of freedom, the physical Higgs after SSB.

After the symmetry breaking, the Lagrangian in Eq. (20) in the vacuum reads:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & \frac{1}{2}(\partial_\mu H)(\partial^\mu H) + \frac{g^2}{4}(v + H)^2 W_\mu^+ W^{-\mu} \\ & + \frac{g^2}{8(\cos\theta_W)^2}(v + H)^2 Z_\mu Z^\mu \\ & + \frac{\mu^2}{2}(v + H)^2 - \frac{\lambda}{16}(v + H)^4 \end{aligned} \quad (24)$$

where the real  $W^\pm$  and  $Z$  fields have been already introduced in Eq. (17). By expanding the mass terms in the Lagrangian and factorizing them, the Higgs potential reads:

$$V_H = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \quad (25)$$

which describes a scalar field with mass  $m_H = \sqrt{2\lambda v^2}$  and self-interaction terms.

In this gauge, the vacuum is invariant under a combination of a  $SU(2)_L$  rotation of an angle  $\alpha$  around the  $z$ -axis and a  $U(1)_Y$  rotation of an angle  $\alpha/2$ :

$$\Phi_0 \rightarrow e^{i\alpha(\frac{1}{2}1 + \frac{\sigma^3}{2})} \Phi_0 \quad (26)$$

As result, after symmetry breaking a combination of weak isospin and weak hypercharge is left unbroken. We can say that the electromagnetic gauge group  $U(1)_{\text{EM}}$ , whose symmetry acts as in Eq. (26) on



the vacuum state, ensures that the photon remains massless. On the other hand, in Eq. (24) the  $W$  and  $Z$  bosons acquire masses, which can be expressed in terms of the coupling constants as  $m_W = gv/2$  and  $m_Z = m_W/\cos\theta_W$ , so that the mass ratio of the weak gauge bosons is fully determined by the weak mixing angle  $\theta_W$ , an important prediction of the SM built with the Higgs doublet.

Finally, an additional scalar particle appears in Eq. (24), the Higgs boson, whose mass  $m_H$  is a free parameter of the SM and is not predicted by the theory.

#### 1.3.4 Fermion Masses and Mixing

The gauge invariant mass terms of fermions in the SM Lagrangian are generated through Yukawa couplings between the  $SU(2)$  Higgs doublet  $\Phi$ , the left-handed fermion doublets and the right-handed fermion singlets. In the form of the Yukawa Lagrangian:

$$\mathcal{L}_{\text{Yukawa}} = - \sum_{f=l,q} y_f [\bar{f}_L \Phi f_R + \bar{f}_R \Phi f_L] \quad (27)$$

where the  $y_f$  are  $3 \times 3$  matrices defining the coupling strengths for all terms. The  $\mathcal{L}_{\text{Yukawa}}$  is gauge invariant since the  $\bar{f}_{L/R} \Phi f_{R/L}$  are  $SU(2)_L$  singlets. When the  $\Phi$  field has a non-zero expectation value,  $\mathcal{L}_{\text{Yukawa}}$  not only describes an interaction between the Higgs field and fermion but the fermions will acquire a finite mass. If we restrict to the electron case:

$$\begin{aligned} \mathcal{L}_e &= -y_e \frac{1}{\sqrt{2}} \left[ (\bar{\nu}, e)_L \begin{pmatrix} 0 \\ v + H \end{pmatrix} e_R + \bar{e}_R (0, v + H) \begin{pmatrix} \nu \\ e \end{pmatrix}_L \right] \\ &= -y_e \frac{(v + H)}{\sqrt{2}} [(\bar{e}_L e_R) + (\bar{e}_R e_L)] = -y_e \frac{(v + H)}{\sqrt{2}} \bar{e}e \quad (28) \\ &= -y_e \frac{v}{\sqrt{2}} \bar{e}e - y_e \frac{H}{\sqrt{2}} \bar{e}e \end{aligned}$$

we find in the last line the electron mass term  $m_e = y_e \frac{v}{\sqrt{2}}$ .

However, after spontaneous symmetry breaking the Lagrangian mass terms are obtained by fixing the gauge and by moving from the interaction basis to the mass basis in which the mass matrices are diagonal via unitarity transformations  $U^{f_{L/R}}$ :

$$U^{d_L} m_d (U^{d_L})^\dagger = m_d^{\text{diag}} \quad U^{u_L} m_u (U^{u_L})^\dagger = m_u^{\text{diag}} \quad (29)$$

The product  $V = U^{u_L} (U^{d_L})^\dagger$  is called the Cabibbo-Kobayashi-Maskawa (CKM) matrix [18, 19] and describes the quark mixing between three quark families occurring in the charged-current weak interactions involving quarks. The CKM matrix is a  $3 \times 3$  unitary matrix:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (30)$$

As a unitary complex matrix, it can be parametrized by four parameters like three mixing angles and one complex CP violating phase. This provides the only source of CP violation in the quark sector.

#### 1.4 THE STRONG SECTOR

##### 1.4.1 Quantum Chromodynamics

The strong interaction between quarks and gluons is described by imposing local gauge SU(3) invariance. The corresponding theory is called *quantum chromodynamics* (QCD), whose formulation follows an analogous construction as the QED seen in Section 1.3.1. A new quantum number, the *color*, is introduced. The global gauge symmetry is promoted to local by introducing the covariant derivative with the vector field  $G^\mu$ , describing the gauge bosons of the (QCD), the *gluons*:

$$D^\mu = \partial^\mu + ig_s G^\mu \quad \text{with} \quad G^\mu = G_a^\mu T^a \quad (31)$$

This defines the structure of interactions between quarks and gluon, where  $g_s$  is the strong coupling constant. The  $T^a$  are the eight generators of the SU(3) group. The quark wave equation is then required to be covariant under *local* SU(3)<sub>c</sub> transformations of the form:

$$\psi \rightarrow \psi' = e^{ig_s \bar{\alpha}(x) \cdot \bar{T}} \psi \quad (32)$$

In the fundamental representation of SU(3), the  $T^a$  generators satisfy the relation:

$$[T^a, T^b] = if^{abc} T^c \quad (33)$$

where the  $f^{abc}$  are the structure constants of the SU(3) group. This property denotes the so-called *non-Abelian* groups and provides the gluon field with an additional term of self-interaction, not present in the QED case:

$$ig_s G_{\mu\nu} = [D_\mu, D_\nu] = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^c \quad (34)$$

The assumption of local SU(3)<sub>c</sub> covariance in Eq. (32) leads therefore to a great deal: it implies that the gluons are massless vector (spin-1) particles and that they interact with themselves via three-gluon and four-gluon vertices.

In the fundamental representation the quarks are described by the triplet  $q = (q_r, q_b, q_g)$ , corresponding to the different color of a given quark type, the QCD Lagrangian is then given by:

$$\mathcal{L}_{\text{QCD}} = \bar{q}_j [i\not{D} - m]_{jk} q_k - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu, a} \quad (35)$$

where  $j$  is the color index and a summation over families is implied. The gluon self-coupling arises from the term  $-\frac{1}{4} G_{\mu\nu}^a G^{\mu\nu, a}$  in Eq. (35) leading to terms of order  $g_s G^3$  and  $g_s^2 G^4$  which describe the required triple and quartic self-couplings.

### 1.4.2 Renormalization

Unlike the QED case, where the EM coupling constant  $\alpha_{\text{EM}}$  falls with decreasing energy scale of the process, in QCD the strong coupling  $\alpha_s = g_s/4\pi$  becomes larger at lower scales, so that perturbative theory breaks down. This violation of the scale invariance is associated to the *renormalization*, i.e. the redefinition of the parameters of the theory at a given energy  $Q$  absorbing this way the ultraviolet divergences appearing in radiative corrections of quantum field theories. This introduces an arbitrary renormalization scale  $\mu_R$  and a dependance of the parameters on this scale appears. The scaling behaviour can be described by the renormalisation group equations (RGE). The running of the strong coupling constant  $\alpha_s$  is determined by the  $\beta$ -function:

$$Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s) \quad (36)$$

The beta function can be computed in perturbation theory. At the 1-loop level calculation we obtain:

$$\beta(\alpha_s) = -\alpha_s^2(Q^2) \frac{33 - 2N_f}{12\pi} \quad (37)$$

where  $N_f$  denotes the number of light quark flavours active at the scale of interest  $\mu$ .

The negative sign of Eq. (37) leads as a consequence that  $\alpha_s$  becomes smaller at increasingly high energies (or small distances), which is the property of the *Asymptotic freedom*. The strong coupling becomes therefore weaker for processes with large momentum transfers, also called *Hard Processes*, and partons can consequently be described with a quasi-free particle model. Combining Eq. (37) in (36), we obtain:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2) \frac{(33 - 2N_f)}{12\pi} \log \frac{Q^2}{\Lambda^2}} \quad (38)$$

The dimensional parameter  $\Lambda$  is an infrared cut-off scale indicating where the perturbative scale is no longer valid. It depends on the renormalization scheme and it is experimentally measured to be  $\Lambda \approx 200$  MeV. The *running* of  $\alpha_s(Q)$  with the scale  $Q^2$  compared to experiments is shown in Figure 2.

It is asymptotic freedom that gives QCD much of its interesting dynamics, and allows to perform perturbative calculations at the high energies of interest at colliders

### 1.4.3 Color Confinement

On the opposite side, the behaviour of the running coupling at low energy leads to the confinement of the quarks inside the hadrons, as anticipated, and the consequent impossibility of having free quarks of gluons. Since the strong interaction bosons, i.e. the gluon fields, are

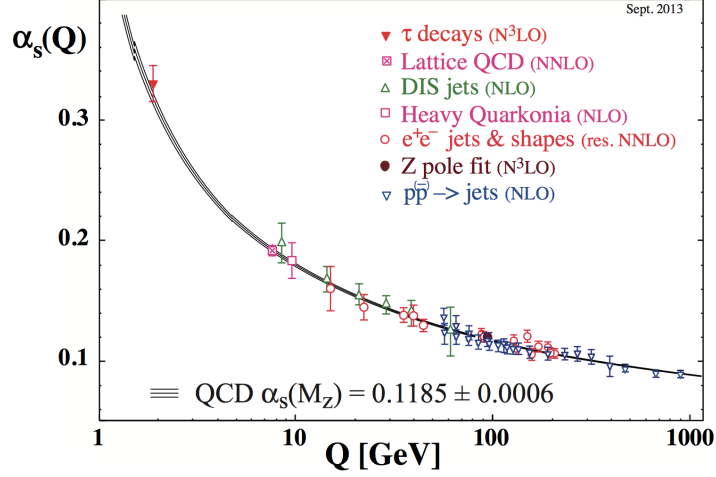


Figure 2: Summary of measurements of  $\alpha_s$  as a function of the energy scale  $Q$ , obtained at different orders in perturbation theory [20].

massless we could expect the strong interaction to be long range as it happens in the QED case, but this appears inconsistent with the observed short range of the color force. At low-momentum transfers,  $qcd$  is so strongly coupled that for a quark pair with increasing potential energy it is more convenient to create a new quark-antiquark pair from the vacuum, and thus a new hadron, instead of separating the quarks themselves. This process is also called *hadronization*.

### 1.5 SUMMARY OF THE STANDARD MODEL

The overall symmetry of the SM is obtained by putting together the results from the previous section, obtaining  $SU(3)_C \times SU(2)_L \times U(1)_Y$ . The final formulation of the SM has 19 free parameters whose value has to be measured experimentally. 18 of them have been already introduced: nine fermion masses (6 quarks and three leptons), the  $\mu, \lambda$  parameters of the Higgs potential, three gauge couplings  $g, g', g_s$  and four CKM matrix parameters. The 19<sup>th</sup> parameter is usually denoted as QCD vacuum angle  $\theta$ , accounting for CP violation of strong interactions, which has not been observed yet.

If we assign a value of  $L_n = +1(-1)$  to each lepton (antilepton) and  $Q_n = +1(-1)$  to each quark (antiquark) and 0 to the other particles, we observe that the total leptonic (quark) number  $L_n(Q_n)$  has to be preserved in the interactions<sup>2</sup>. The individual lepton numbers ( $L_e, L_\mu, L_\tau$ ) would be conserved if the neutrinos were massless. Being the neutrino flavour oscillations observed by experiments [21], a violation of lepton number is present.

The strong interaction of gluons and quarks comes along with the phenomenon of confinement, so that only colorless states are allowed as

<sup>2</sup> Nonetheless, in SM there are anomalies at the loop level for which L's are instead violated, which are beyond this work's reach.

physical hadrons. In the phenomenological perspective, it is more natural to consider the *baryon* number instead of the quark number. Baryons are composed of three quarks and, using the fundamental representation 3, are defined with  $\epsilon^{abc}q_aq_bq_c$ . In the same representation, the *mesons* composed of two quarks of opposite color are defined with  $q_a\bar{q}^b$ . As bounded colorless states, those combinations are as a matter of fact the only ones experimentally observed.

## 1.6 SHORTCOMINGS OF THE STANDARD MODEL

The Standard Model successfully describes strong, weak and EM interactions up to energy of several hundreds of GeV. The theoretical predictions of the SM have continuously been tested and confirmed with increasing precision, other than becoming more and more accurate due to improved technical methods. The theory has also proven a high level of self-consistency in indirect measurements. Despite this success, there are several theoretical problems and experimental results not addressed by the Standard Model in its current formulation suggesting that the SM is only an effective approximation at lower energies of a more complete theory able to explain the whole spectrum of observations. The interest in searches for physics *beyond the Standard Model* (BSM) is therefore originating from these unsolved problems, some of which are briefly summarized here.

**Gravity** The description of gravity is not included in the SM. Gravitational effects can be neglected up to energies below the Planck scale ( $M_P = (8\pi G_N)^{-1/2} = 10^{18}$  GeV), which therefore marks a limit to the validity of the SM. A massless 2-spin particle, called in theory the *graviton*, can provide an effective description of gravity within the SM, however no valid theory exists so far.

**Neutrino Masses** The presence of the neutrino masses is established by the observation of neutrino flavour oscillations [21], requiring a mass difference between the neutrino generations, although the neutrino masses have not been directly measured and a mass term is not considered in the SM. The neutrino mass could be accommodated via the so-called *Seesaw* mechanism, whose simplest formulation introduces in the SM Lagrangian a new gauge singlet chiral fermion,  $\nu_R$ . In the Majorana neutrino description, the neutrino would be its own anti-particle ( $\nu = \bar{\nu}$ ), and some new physics at high energy would be therefore needed.

**Baryon Asymmetry** Our current theory describing the creation of the Universe predicts the matter and antimatter to have been produced in equal amount, while the obvious observation is of a Universe predominantly matter-like. CP-violation within electro-weak interactions denoted by the phase in the CKM matrix is not strong enough to explain the observed asymmetry in the baryogenesis. A connected problem can be found in the absence of CP-violation in the strong sector: a CP-violating term as  $F_{\mu\nu}\tilde{F}^{\mu\nu}$  is consistent with

gauge symmetry of QCD Lagrangian but not consistent with current measurements.

**Mass Hierarchy** The SM is completely specified with 19 parameters, out of them 9 fermion masses whose hierarchical mass structure ranges within  $(0.5 \cdot 10^{-3}, 173)$  GeV. Moreover, the fermions come in three different families. The fermion mass hierarchy and the fixed number of families are not explicitly justified by the theory, which also does not address the unnatural spanning of the mass values over five orders of magnitude. Albeit not a problem per se, this and other possible examples of some *naturalness* shortcoming of the SM may be an indication of unknown principles underlying the existence of a deeper structure.

The shortcomings listed above do not directly point to an energy scale at which those issues might be addressed. Three other unexplained issues of the SM pave the way for the development of theories for new physics which could manifest itself at the scale accessible by the LHC. They are further discussed below.

#### 1.6.1 *Dark Matter*

Several astrophysical observations provide compelling evidence that most of the matter in the universe is non visible, not carrying electric or colour charge and interacting only via gravitation and weak nuclear forces. The portion of such a non-baryonic matter which cannot be accounted for by any SM particle is named *Dark Matter* (DM). First indications came in the 1930's from measurements of the rotational speeds of galaxies [22]. Moreover, recent measurements from the analysis of the cosmic microwave background [23, 24] indicated that the universe is dominated by dark energy for  $\sim 68\%$  and dark matter for  $\sim 27\%$ , leaving only  $\sim 5\%$  to the already known ordinary matter. Several models explaining DM have been proposed [25, 26], among which the *Weakly Interacting Massive Particles* (WIMPs) one is particularly motivated, as it proposes a mass of the WIMPs of order  $m_\chi \sim 100$  GeV, under certain assumptions [24].

#### 1.6.2 *Gauge Coupling Unification*

Grand Unification Theories (GUT) attempt to embed the description of all the interaction forces (firstly those within the SM) in a larger and broader theory via the introduction of a larger symmetry group containing the SM gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$ . The first formulation exploits the group  $SU(5)$  [27], while subsequent theories propose  $SO(10)$  [28] or  $E_6$  [29]. The symmetry is expected to be unbroken at a higher energy scale where the gauge coupling constants unify in a coupling  $\alpha_G$ . However, the current prediction of the evolution of the gauge couplings obtained using renormalisation group equations (RGE) shows that SM forces do not unify at the same energy, while supersymmetric

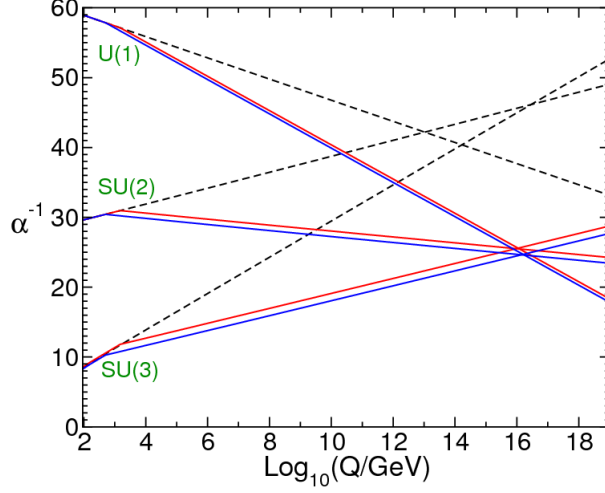


Figure 3: The two loop evolution of the inverse gauge couplings  $\alpha_a^{-1}(Q)$  in the SM (dashed lines) and in the MSSM (solid lines). Figure taken from [30]

theories (which will be introduced in Chapter 2) offer such a possibility, as shown in Figure 3.

### 1.6.3 Hierarchy Problem

The Higgs propagator receives quantum corrections originated by the virtual effects of each particle coupling to the Higgs field, including the Higgs itself. The Higgs boson mass can therefore be expressed as:

$$m_H^2 = m_{H,0}^2 + \delta m_H^2 \quad (39)$$

The largest contribution comes from the fermion with the largest coupling, the top quark:

$$(\delta m_H^2)_{\text{top}} = -\frac{3\lambda_{\text{top}}^2}{8\pi^2} \Lambda^2 + \dots \quad (40)$$

The integration over the loop is cut-off at a scale  $\Lambda$ , the energy up to which the Standard Model is an effective theory.  $\lambda$  is the Yukawa coupling of the fermion to the Higgs boson (here  $\lambda_{\text{top}}$  for the top quark)<sup>3</sup>. Eq. (40) exhibits a quadratic divergence in the UV sector. The neglected terms grow at most logarithmically with  $\Lambda$  and proportional to  $m_f^2$  ( $\mathcal{O}(m_f^2 \ln(\frac{\Lambda}{m_f}))$ ), for the generic  $f$  fermion. Similar corrections arise also from gauge-boson loops, as shown in Figure 4b. The correction values depends therefore on the choice made for the cut-off scale  $\Lambda$ . Abiding by the SM being valid up to the Planck scale,  $M_P = 10^{19}$  GeV, the corrections quickly become larger than the tree-level value, resulting up to 30 orders of magnitude larger than the measured  $m_H^2$ . In order to retrieve the measured value of the Higgs mass, the bare value and the corrections have to exactly cancel to an incredible precision (up to 36

3 The factor 3 in Eq. (40) takes in account the color for quarks.

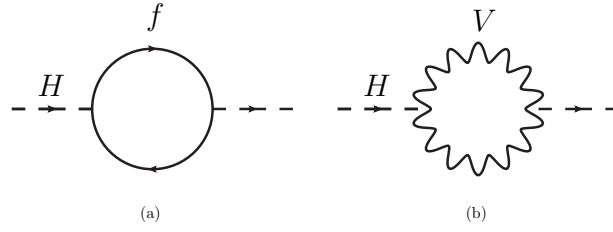


Figure 4: SM diagrams showing one-loop quantum corrections to the Higgs mass due to fermions (a) and bosons (b).

digits). The issue of such a precise cancellation is known as *fine-tuning*. Even though it is not directly forbidden that physics parameters are fine-tuned, such a coincidence instills the doubt that some New Physics mechanisms are present to keep the Higgs boson mass at EW scale.



## SUPERSYMMETRY

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The several shortcomings of the SM have stimulated the formulation of different theories of New Physics, attempting to provide suitable solutions to the different issues. The theory of Supersymmetry (SUSY) is here introduced as possible extension of the SM, while highlighting the phenomenology of the theory and discussing its current constraints.

### 2.1 INTRODUCTION

Supersymmetry is a space-time symmetry relating boson and fermions, particularly between particles with identical quantum numbers but the spin differing by  $\pm\frac{1}{2}$ . This concept has been introduced after the revision of the Coleman-Mandula *no-go* theorem [31] on symmetry groups for quantum field theories. The theorem states that for any theory with a finite number of particles the symmetry group is the direct product of the internal symmetry group<sup>1</sup> and the Poincaré group. The direct consequence is that any further symmetry which is external to the Lorentz group must be trivial. However, this result only considers symmetries involving bosonic generators, like all the symmetries in the Standard Model, and it does not apply to conserved charges transforming as spinors, i.e. spinorial symmetries whose generators have half-integer spin had not been considered by the theorem. The extension of the Coleman-Mandula theorem by Haag, Lopuszanski and Sohnius [32] stated that Poincaré group could be extended by a new external symmetry with spin- $\frac{1}{2}$  generators without breaking the previous constraint. Alternatively, we can say that space-time and internal symmetries are still independent, but transformations between the spin states are allowed. Such transformations are described by spinor operators  $Q_\alpha$  modifying the spin of a state:

$$Q_\alpha |J\rangle = |J \pm \frac{1}{2}\rangle \quad (41)$$

This fermionic extension is known as Supersymmetry (SUSY). A Supersymmetric theory interchanges fermions and bosons. This leads to the prediction of the existence of a supersymmetric partner for every SM particle. The particle content of the Universe is therefore doubled by including Supersymmetry.

### 2.2 SUPERSYMMETRY ALGEBRA

Supersymmetry is the extension of the Poincaré group including fermionic symmetries. The operators  $Q_\alpha$  generate a *graded* Lie algebra part of the

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<sup>1</sup> i.e. the gauge group

*super Poincaré algebra*. If we consider the simplest SUSY version invariant under transformations of the group  $U(1)$ , the generators  $Q$  and its hermitian conjugate  $Q^\dagger$  must satisfy the following commutation and anti-commutation rules:

$$\{Q_a, Q_b\} = 0 \quad (42a)$$

$$\{Q_a, Q_b^\dagger\} = 2(\sigma^\mu)_{ab} P_\mu \quad (42b)$$

$$[P_\mu, Q_a] = 0 \quad (42c)$$

with  $P^\mu$  is the four-momentum vector generator of space-time translations. It can be seen how the operator  $Q$  raises the spin by  $\frac{1}{2}$  while  $Q^\dagger$  lowers it by  $\frac{1}{2}$ .

The single-particle states of a supersymmetry theory are grouped in irreducible representations of the algebra, called *supermultiplets*. Two states belong to the same supermultiplet if one can be generated from the other by some combination of  $Q$  and  $Q^\dagger$ . A supermultiplet contains both boson and fermion states, which are called *superpartners*, such that the number of boson ( $n_b$ ) and fermion ( $n_f$ ) degrees of freedom are equal. From Eq.(42c), the generators of the SM gauge group commute with the SUSY generators, causing the particles in the same supermultiplet to have the same quantum numbers (except the spin). Moreover, by Eq.(42c)  $Q$  commutes also with  $P^2 = P^\mu P_\mu$ , so that particles and their superpartners must have same eigenvalues of the operator, i.e. equal masses. The simplest supermultiples satisfying the condition  $n_b = n_f$  are:

- *Chiral supermultiplets* containing one Weyl spinor with 2 spin-helicity states, and two real scalars (each with one degree of freedom) typically assembled into a complex scalar field.
- *Gauge supermultiplets* containing a massless spin-1 boson and a spin-1/2 Weyl fermion.

The chiral and gauge supermultiplets suffice to accommodate all fundamental SM particles. If gravity is included, the graviton (a spin-2 particle) must have a spin-2/3 superpartner called *gravitino*.

## 2.3 THE MINIMAL SUPERSYMMETRIC STANDARD MODEL

The case of  $N = 1$  SUSY, with just a single transformation generator, is basically the only possible configuration that permits chiral representations. Such a SUSY extension of the SM is named the Minimal Supersymmetric Standard Model (MSSM).

### 2.3.1 Particle Content of the MSSM

In the MSSM a new fermion (boson) is associated to every boson (fermion) of the SM, being its *superpartner*.

The SM fermions have scalar superpartners whose name is the result of the SM fermion name with a "s" for "scalar" added in front, so that

| <b>Supermultiplets</b>              |           | <b>Bosons</b>                  | <b>Fermions</b>                    | <b>SU(3)<sub>C</sub></b>    | <b>SU(2)<sub>L</sub></b> | <b>U(1)<sub>Y</sub></b> |
|-------------------------------------|-----------|--------------------------------|------------------------------------|-----------------------------|--------------------------|-------------------------|
| <i>Chiral Multiplets</i>            |           | spin-0                         | spin-1/2                           |                             |                          |                         |
| squarks, quarks<br>(x 3 families)   | Q         | ( $\tilde{u}_L, \tilde{d}_L$ ) | ( $u_L, d_L$ )                     | <b>3</b>                    | <b>2</b>                 | $\frac{1}{6}$           |
|                                     | $\bar{u}$ | $\tilde{u}_R^*$                | $u_R^\dagger$                      | <b><math>\bar{3}</math></b> | <b>1</b>                 | $-\frac{2}{3}$          |
|                                     | $\bar{d}$ | $\tilde{d}_R^*$                | $d_R^\dagger$                      | <b><math>\bar{3}</math></b> | <b>1</b>                 | $\frac{1}{3}$           |
| sleptons, leptons<br>(x 3 families) | L         | ( $\tilde{\nu}, \tilde{e}_L$ ) | ( $\nu, e$ )                       | <b>1</b>                    | <b>2</b>                 | $\frac{1}{2}$           |
|                                     | $\bar{e}$ | $\tilde{e}_R^*$                | $e_R^\dagger$                      | <b>1</b>                    | <b>1</b>                 | 1                       |
| Higgs, higgsinos                    | $H_u$     | ( $H_u^+, H_u^0$ )             | ( $\tilde{H}_u^+, \tilde{H}_u^0$ ) | <b>1</b>                    | <b>2</b>                 | $\frac{1}{2}$           |
|                                     | $H_d$     | ( $H_d^0, H_d^-$ )             | ( $\tilde{H}_d^0, \tilde{H}_d^-$ ) | <b>1</b>                    | <b>2</b>                 | $-\frac{1}{2}$          |

Table 3: Chiral supermultiplets and field representation of the MSSM with their quantum numbers [30].

| <b>Supermultiplets</b>    |  | <b>Bosons</b> | <b>Fermions</b>              | <b>SU(3)<sub>C</sub></b> | <b>SU(2)<sub>L</sub></b> | <b>U(1)<sub>Y</sub></b> |
|---------------------------|--|---------------|------------------------------|--------------------------|--------------------------|-------------------------|
| <i>Gauge Multiplets</i>   |  | spin-1        | spin-1/2                     |                          |                          |                         |
| Gluons, gluinos           |  | g             | $\tilde{g}$                  | <b>8</b>                 | <b>1</b>                 | 0                       |
| W bosons, winos           |  | $W^\pm, W^0$  | $\tilde{W}^\pm, \tilde{W}^0$ | <b>1</b>                 | <b>3</b>                 | 0                       |
| $\gamma$ , Z boson, binos |  | $B^0$         | $\tilde{B}^\pm$              | <b>1</b>                 | <b>1</b>                 | 0                       |

Table 4: Gauge supermultiplets and field representation of the MSSM and their quantum numbers [30].

*squarks* are the partner of the quarks likewise *sleptons* are the partner of the leptons. The left-handed and the right-handed parts of the SM fermions belong to different supermultiplets since they transform differently under gauge transformations. Therefore, each fermion has 2 complex scalar superpartners, one for each handedness. For neutrinos, since they have only left-handed component in the SM, this distinction is not made.

The Higgs and gauge bosons have fermionic superpartners whose naming convention is to add "ino" to the end of the SM boson name, resulting in the *Higgsinos* and the *gauginos* (winos, binos, gluinos). The Higgs boson is a spin-0 particle, therefore it fits into chiral supermultiplets. However, introducing a Higgs doublet in the MSSM leads to a higgsino. Any triangular anomalous terms arising as the result of the introduction of this new particle can be cancelled only by terms involving a corresponding particle with opposite hypercharge. A second higgsino is therefore introduced through a second Higgs doublet that gives mass to the down-type quarks:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad (43)$$

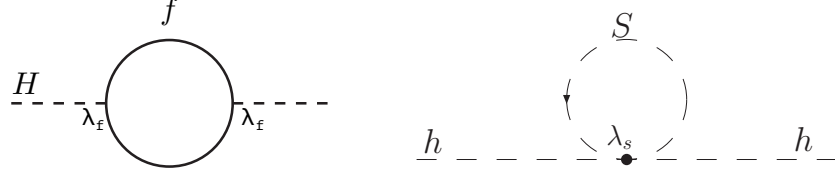


Figure 5: SM diagrams showing one-loop quantum corrections to the Higgs mass due to fermions (left) and bosons (right).

The chiral and gauge supermultiplets discussed above make up the particle content of the MSSM, which is summarized in Table 3 and 4.

### 2.3.2 Solution to the SM shortcomings

#### *Higgs finetuning*

A first important achievement of the Supersymmetry extension of the SM is the immediate cancellation of the quadratically sensitive ( $\Lambda_{UV}$ ) correction to the Higgs mass of Eq.(40).

Supersymmetry states that for every chiral fermion two complex scalar fields exist. Neglecting terms growing logarithmically, the one-loop radiative correction due to a scalar particle shown in Figure 7 contributes to the Higgs mass as:

$$(\delta m_H^2)_s = \frac{\lambda_s}{16\pi^2} \Lambda^2 \quad (44)$$

Considering two corrections as in Eq.(44) and combining them with (40) for a generic fermion  $f$ , we arrive at:

$$\delta m_H^2 = \frac{1}{8\pi^2} (|\lambda_f|^2 - \lambda_s) \Lambda^2 \quad (45)$$

The cancellation holds if the dimensionless couplings satisfy the condition ( $|\lambda_f|^2 = \lambda_s$ ). This relationship holds in unbroken SUSY, where particles from the same supermultiples carry the same mass.

#### *Grand Unified Theories*

By extending the SM with supersymmetry, the running of the gauge couplings constants can be changed so they all meet in one point provided the masses of the sparticles are in the range of 100 GeV to 10 TeV - meaning that GUT theory are supposed to satisfy SUSY at low energies. SUSY modifies the RGE above the superpartners mass scale and such a configuration allows for a direct unification of all three forces at the GUT energy scale of  $10^{16}$  GeV. A comparison of the couplings evolution in the SM and the MSSM is shown in Figure 3.

## 2.4 SUSY BREAKING

If supersymmetry was an exact unbroken symmetry, the Standard Model particles and their respective supersymmetric partners would have iden-

tical masses. In the electron case, the *selectrons*  $\tilde{e}_R$  and  $\tilde{e}_L$  should have masses exactly equal to  $m_e \simeq 0.51$  MeV, and that should work accordingly for the other sleptons and squarks. Moreover, there would also have to be a massless gluino and photino. Since no superpartners have been discovered at the explored energy ranges, supersymmetry must be *broken* in the vacuum state allowing the sparticles to have higher masses than their Standard Model partners.

The mechanism whereby SUSY is broken is currently unknown, although there exist theoretical models explaining it (e.g. the *D-term* [33] and the *F-term* [34] SUSY breaking mechanisms). Usually, phenomenological assumptions are used. Similarly to the SM case, in which the Higgs sector is introduced to break the EW symmetry, it is also not possible to break supersymmetry in the "visible" sector of SM particles and their superpartners. A separate (so-called "hidden") sector is needed to allow the breaking to happen, and some interaction to transmit the breaking to the visible sector is therefore needed.

Regardless of the specific breaking mechanism, "soft" breaking mechanisms must be considered within the MSSM in order to keep the supersymmetry solution to the hierarchy problem. After the breaking terms are added explicitly in the MSSM, the effective Lagrangian of the broken MSSM then reads:

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (46)$$

With  $\mathcal{L}_{\text{SUSY}}$  containing all the gauge and Yukawa interactions and preserving SUSY invariance, and  $\mathcal{L}_{\text{soft}}$  violating SUSY but containing only mass terms and couplings with positive mass dimensions. The soft supersymmetry breaking term results in twice the corrections to the Higgs scalar masses given by Eq.(44) and leaves the only residual terms logarithmic in the ultraviolet momentum cutoff  $\Lambda$  (and not quadratic terms as in the SM) as correction, of the form:

$$\delta m_H^2 \sim m_{\text{soft}}^2 \left[ \frac{\lambda}{16\pi^2} \ln \frac{\Lambda}{m_{\text{soft}}} \right] \quad (47)$$

where  $m_{\text{soft}}$  is the typical mass scale of the soft SUSY-breaking terms. Adopting a scale of  $\Lambda \sim m_{\text{proton}}$  and  $\lambda \sim 1$ , it turns out that unnatural cancellations between the bare mass and the corrections in Eq.(39) are not needed if  $m_{\text{soft}}$  does not exceed the TeV scale, which scores an important point in favour of expecting the SUSY particles to be produced at the LHC.

As the exact mechanism behind the soft SUSY breaking is unknown, all terms allowed after soft SUSY breaking are included in the Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{SUSY}}^{\text{MSSM}} = & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + \text{c.c}) \\ & - \tilde{Q}^\dagger m_Q^2 \tilde{Q} - \tilde{L}^\dagger m_L^2 \tilde{L} - \tilde{u}^\dagger m_u^2 \tilde{u} - \tilde{d}^\dagger m_d^2 \tilde{d} - \tilde{e}^\dagger m_e^2 \tilde{e} \\ & - (\tilde{u} a_u \tilde{Q} H_u - \tilde{d} a_d \tilde{Q} H_d + \tilde{e} a_e \tilde{L} H_d + \text{c.c}) \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c}) \end{aligned} \quad (48)$$

The first line describes the masses of the gauginos: gluino ( $M_3$ ), winos ( $M_2$ ) and bino ( $M_1$ ). The second line contains the sfermion mass terms with  $\mathbf{m}_Q^2, \mathbf{m}_L^2, \mathbf{m}_u^2, \mathbf{m}_d^2, \mathbf{m}_t^2$  being the hermitian, possibly complex  $3 \times 3$  mass matrices. The third line contains terms of trilinear scalar couplings between the sfermions and the Higgs bosons, much like the Yukawa coupling of the Standard Model. The  $\mathbf{a}$  are complex  $3 \times 3$  mass matrices. The last line are contributions to the Higgs potential coming from SUSY breaking, with  $m_{H_u}^2, m_{H_d}^2, b$  having squared mass dimension.

After breaking SUSY,  $\mathcal{L}_{\text{SUSY}}$  ends up with 111 parameters, that can be reduced to 105 independent parameters with the redefinition of some of the fields. These parameters include masses, mixing angles, and phase combinations invariant under reparametrizations.

#### 2.4.1 *R-parity*

The superpotential included in the MSSM Lagrangian is minimal in the sense that it is sufficient to produce a phenomenologically feasible model. It is however possible to insert additional terms that are gauge-invariant and renormalizable but they violate either baryon number (B) or lepton number (L), which marks a great difference with respect to the SM case. The corresponding superpotential terms read:

$$\begin{aligned} W_{\Delta L=1} &= \frac{1}{2} \lambda \epsilon_{ij} L^i L^j e^c + \lambda' \epsilon_{ij} L^i Q^j d^c + \mu' L^i H_d^j \\ W_{\Delta B=1} &= \frac{1}{2} \lambda'' \epsilon_{ij} u^c d^c d^c \end{aligned} \quad (49)$$

the terms proportional to  $\lambda, \lambda'$  and  $\mu'$  violate lepton number by one unit, whereas the term proportional to  $\lambda''$  violates baryon number by one unit. The conservation of these numbers is strongly constrained by many experimental results, the strongest being the limit on the lifetime of the proton. In fact, a non-zero  $\lambda'$  and  $\lambda''$  would lead to the proton decay process  $p \rightarrow e^+ \pi^0, \mu^+ \pi^0, \nu \pi^+, \nu K^+, \dots$ . The current limit on proton decay [35] imply that either the terms in the Lagrangian violating B and L have very small couplings, or they are not admitted. The terms could anyway be set to zero, however non-perturbative effects break the conservation of B and L in any case.

An appropriate solution is to impose a new discrete symmetry eliminating the possibility of terms violating B and L, by requiring the superpotential to be invariant under a new parity, called *R-parity*:

$$R = (-1)^{3(B-L)+2s} \quad (50)$$

with B, L and s baryon number, lepton number and spin respectively.

With this definition, SM particles have R-parity +1, while SUSY particles -1, distinguishing between SM and SUSY particles. If R-parity is exactly conserved, then all the superpotential terms in Eq.(49) must vanish.

The conservation of the R-parity has important phenomenological consequences:

- The interaction of SM particles can produce only pairs of SUSY particles, and heavier SUSY particles can decay only into lighter SUSY particles.
- A SUSY particle must decay into an odd number of SUSY particles with  $R = -1$  and additional SM particles.
- The lightest supersymmetric particle (LSP) is set to be stable, as SUSY particles have to decay to particle with  $R = -1$ , making it a natural candidate for DM.
- In collider experiments we expect large missing energy from the LSP escaping the detectors volume undetected.

#### 2.4.2 Higgs sector in the MSSM

From SUSY breaking it is possible to derive important predictions on the Higgs boson. In the MSSM the EW symmetry breaking is complicated by the presence of the two Higgs doublets  $H_u = (H_u^+, H_u^0)$  and  $H_d = (H_d^0, H_d^-)$ , which are included in the scalar potential  $V$ . Demanding that the minimum of the potential should break EW symmetry in accord to the observations, we can use the freedom to make gauge transformations to simplify the analysis. The charged components of the Higgs doublets can be chosen to be zero,  $H_u^+ = H_d^- = 0$ , so that the potential  $V$  is left at [30]:

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (bH_u^0H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_d^0|^2)^2 \quad (51)$$

where  $b$  and  $H_u^0H_d^0$  can be chosen real and positive. The Higgs doublets acquire different vacuum expectation values  $\langle H_u^0 \rangle = v_u$  and  $\langle H_d^0 \rangle = v_d$ , whose ratio is normally referred to as:

$$\tan\beta \equiv \frac{v_u}{v_d} \quad (52)$$

There are 8 degrees of freedom (d.o.f.) due to the presence of the Higgs doublets. The mass of the  $W$  boson is now given by  $m_W^2 = \frac{g^2}{4}(v_u^2 + v_d^2)$  leaving three free parameters:  $\tan\beta$ , the pseudoscalar mass  $m_A$  and  $\text{sgn}(\mu)$ . The *value* of  $\mu$  can be fixed to match the observed  $Z$  boson mass, since:

$$m_Z^2 = 2 \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2 \quad (53)$$

The remaining 5 d.o.f. are manifested as 5 Higgs bosons:

- the CP-even neutral scalars  $h^0$  and  $H^0$ .
- the CP-odd neutral scalar  $A^0$ .
- two charged Higgs bosons  $H^+, H^-$ .

The masses of four of the Higgs bosons,  $H^0, A^0, H^+, H^-$  can be arbitrarily large. The mass of the lightest Higgs,  $h^0$  has a theoretical upper limit given at tree-level by

$$m_{h^0}^2 \leq m_Z |\cos(2\beta)| \quad (54)$$

implying that the three-level mass of the Higgs boson should be lower than 91 GeV, in contrast with the observed value of  $\sim 125$  GeV. After including radiative corrections the Higgs mass increases, but is generally expected to stay lower than 150 GeV for generic supersymmetric theories - assuming that all sparticles that contribute to  $m_{h^0}^2$  in loops have masses not exceeding 1 TeV.

### 2.4.3 Mass spectrum

The sparticle mass spectrum is obtained from evolving the mass parameters defined in soft symmetry breaking Lagrangian at some very high energy scale  $Q_0$ , down to the EW scale. The parameter values at the EW scale can be used to extract physical masses, cross sections or other quantities.

#### *Gaugino Mixing*

Due to the EW symmetry breaking, higgsinos and electroweak gauginos mix into mass eigenstates. The electrically neutral states ( $\tilde{H}_u^0, \tilde{H}_d^0, \tilde{B}, \tilde{W}^0$ ), combine into four mass eigenstates referred to as *neutralinos* ( $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0$  and  $\tilde{\chi}_4^0$ ). The two charged gauginos ( $\tilde{W}^\pm$ ) and the two charged higgsinos ( $\tilde{H}_u^\pm$  and  $\tilde{H}_d^\pm$ ) combine to form two mass eigenstates with charge  $\pm 1$  called *charginos* ( $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^\pm$ ). The mass ordering of the sparticles follow the increasing index convention, where the lowest index denotes the lightest sparticle. The lightest neutralino,  $\tilde{\chi}_1^0$ , is typically assumed to be the lightest supersymmetric particle (LSP), unless the gravitino is lighter *or* R-parity is violated.

The mixing of the higgsinos and gauginos into neutralinos and charginos depends on the parameters  $M_1, M_2$  from Eq.(48),  $\mu$  from Eq.(51) and from  $\tan\beta$  from Eq.(52).

If  $m_Z \ll |M_1, M_2| \ll |\mu|$ , then the two lightest neutralino mass eigenstates are gaugino-dominated, one being very nearly "bino-like"  $\tilde{\chi}_1^0 \approx \tilde{B}$  and the other being "wino-like"  $\tilde{\chi}_2^0 \approx \tilde{W}^0$ , while the lightest chargino mass eigenstate is only "wino-like"  $\tilde{\chi}_1^\pm \approx \tilde{W}^\pm$ . The two heavier neutralinos,  $\tilde{\chi}_3^0, \tilde{\chi}_4^0$ , and the heaviest chargino,  $\tilde{\chi}_2^\pm$  are dominated by the neutral and charged higgsinos, respectively, being "higgsino-like".

If instead  $\mu \ll |M_1, M_2|$ , then the two lightest neutralinos  $\tilde{\chi}_{1,2}^0$  and the lightest chargino  $\tilde{\chi}_1^\pm$  are "higgsino"-like, while the two heavier neutralinos,  $\tilde{\chi}_{3,4}^0$  and the heaviest chargino,  $\tilde{\chi}_2^\pm$  are largely gaugino dominated.

#### *Gluinos, Squarks and Sleptons*

Since the gluino  $\tilde{g}$  is a colour-octet fermion, it cannot mix with any other MSSM particle, even if R-parity is violated. In most models the



gluino mass is considerably heavier than the lighter neutralinos and charginos.

The scalar squark and slepton gauge eigenstates can mix among each other if they have the same electrical charge, R-parity, and colour quantum numbers. However, most of the mixing angles are predicted to be very small for the general hypothesis of flavour-blind soft parameters of the MSSM. Therefore, mixing of the sfermions in the first two families is generally neglected. On the other hand, the third family squarks and sleptons can have substantial mixing between the left-handed and right-handed states, producing very different masses compared to their first- and second-family counterparts, because of the effects of large Yukawa couplings. These pair mixings are taken into account in the MSSM.

## 2.5 SUSY PHENOMENOLOGY

The explicit breaking of the mass degeneracy in the MSSM introduces 105 additional parameters which are added to the theory. In addition to the parameters of the Standard Model, the MSSM has thus a 124-dimensional parameters space. It is therefore crucial to overcome the difficulty of dealing with such a high dimensional parameter space. Many of the phenomenological analyses of the MSSM assume that the 105 parameters reduce to a smaller number at high scale. On top of that, what can be produced at a collider experiment depends on the masses at the weak scale and the mixing matrices.

For any given mass, the most abundantly produced sparticles will be squarks and gluinos, whose coupling to the coloured particles in the proton is the strongest. The production cross-section of sparticles at a centre-of-mass energy  $\sqrt{s} = 13$  TeV is shown in Figure 6. The dominant decay of these particles is  $\tilde{q} \rightarrow q\tilde{\chi}_1^0$  and  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ , leading to an experimental signature of jets and missing energy.

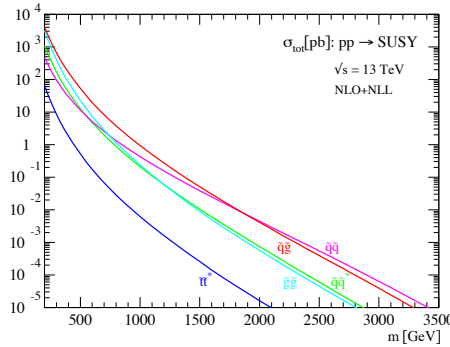


Figure 6: NLO+NLL production cross sections for the case of equal degenerate squark and gluino masses as a function of mass at  $\sqrt{s} = 13$  TeV, from [36]

In the next sections, the two simplified approaches to the search for SUSY of interest in this work are presented. A variety of other

models formulated in order to have a simplification of the MSSM that are exploitable in collider experiments can be found in literature.

### 2.5.1 *The Phenomenological MSSM*

The phenomenological Minimal Supersymmetric Standard Model (pMSSM) [37, 38] is a simplification of the MSSM that has gained popularity after the first negative results of the SUSY search program at the LHC. The number of free parameters is reduced from 105 to 19 in the pMSSM by applying only few experimentally-driven conditions. The reduction is based on three assumptions:

- no sources of CP-violation are included and all phases in the  $\mathcal{L}_{\text{soft}}$  are assumed to be zero.
- no flavour-changing-neutral-currents (FNCN) are included. Sfermion mass matrices and trilinear couplings are assumed to be diagonal to avoid any new FNCN-term.
- 1<sup>st</sup> and 2<sup>nd</sup> generation of sfermions are mass-degenerate and the two generations are assumed to have the same mass.

Those three assumptions greatly reduce the number of free parameters leaving only 19 of them:  $\tan\beta, \mu, M_A, M_{1,2,3}$ , the 10 mass parameters of the sfermions and the trilinear couplings for third generations  $A_t, A_b, A_\tau$ . The phenomenology of the SUSY products is therefore easier to be investigated, since only 19 parameters have to be varied.

### 2.5.2 *Simplified Models*

An alternative approach pursued at collider experiments in order to define a strategy for SUSY searches, is to rely on scenarios called *simplified models* [39, 40]. As the name denotes, such models oversimplify the SUSY parameter space and are therefore not descriptive for most of the SUSY scenarios. Nevertheless, they are useful for different purposes: to identify the reach of the search strategies, as reduced parameter space can be fully explored at the LHC and they can predict very specific detector responses; the results can be used in setting the limits on larger models [41]; finally, simplified models in which only one type of particle is accessible are further motivated by scenarios of split supersymmetry [42].

Simplified models use effective Lagrangians including only a subset of particles and interactions while integrating out the heavier particle content. Specifically, a simplified model Lagrangian will describe pair-production of only one or two types of sparticles, e.g. the gluino or the squark, that can be produced at the LHC. An example can be:

$$\mathcal{L} = \frac{\lambda_i^2}{M_i^2} \tilde{g} q_i \bar{q}_i \tilde{\chi}^0 + \text{h.c.} \quad (55)$$

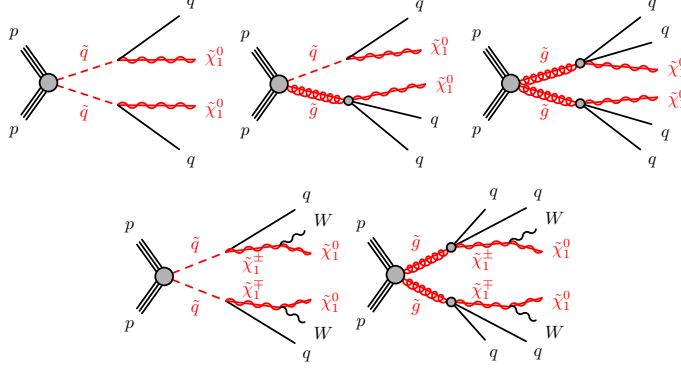


Figure 7: Examples of diagrams for simplified models of squark and gluino pair-production with direct decays (top row), or decaying via an intermediate sparticle  $\tilde{\chi}_1^\pm$  (bottom row). No distinction between quarks flavours and between particles and antiparticles is made.

where  $i$  runs over the quark flavours,  $\lambda_i$  is the Yukawa coupling for the quark-gluino-neutralino vertex and  $M_i$  is the effective scale of the interaction.

Unlike other simplifications, e.g. the pMSSM, containing many different decay-chains of sparticles as in the pMSSM, in simplified models the pair-produced sparticles will normally have only one decay mode with a 100% branching fraction. The decay of the sparticles are motivated by similar decays in the MSSM. The number of free parameters in simplified models is normally reduced to two, such as the mass of the sparticle or the mass difference between sparticles in the decay chain.

Although the simplified models are widely used when searching for SUSY at the LHC, several drawbacks must be noted. In case of certain models, e.g. squark-pair production, the cross-section is strongly dependent on the parameters not considered, such as the gluino mass. Moreover, the assumption of the 100% BR is an oversimplification.

## 2.6 EXPERIMENTAL CONSTRAINTS ON SUSY

Several constraints on SUSY arise both from direct searches conducted at previous colliders (LEP, Tevatron) and dark matter detection experiments, and indirectly from precision measurements that would effectively differ from the SM expectations if SUSY was present.

Limits on direct production of sparticles were set by using specific models which are not easily translated to different scenarios. Limits set by ATLAS or CMS will be discussed while presenting the results obtained in this thesis. R-parity violating models are ignored.

### *Direct Limits at Colliders*

At the Large Electron-Positron (LEP) collider at CERN, the SUSY searches mainly focused on sleptons, excluded up to masses of masses of 80 GeV to 100 GeV by DELPHI [43] and ALEPH [44]. A combination of

SUSY searches at LEP set a limit of 47 GeV on the lightest neutralinos and up to 92 GeV for lightest chargino [45]

The CDF and D0 experiments at the Tevatron had an extensive SUSY searches program, setting limits on many different models. In the strong sector, the search for squarks and gluinos set limit up to 400 GeV on the sparticle masses in channel with hard jets and missing transverse momentum [46, 47], exceeding the limits placed by LEP.

#### *Astrophysical Constraints*

Constraints arising from astrophysical measurements are mainly placing restrictions on the lightest supersymmetric particle LSP as a stable WIMP, i.e. on the assumption that LSP is the origin of the dark matter. A stringent limit on SUSY comes from the observed dark matter *relic density*. The model assumes that DM is only a thermal relic from the early Universe, when an equilibrium between creation and annihilation of DM was in place. After the expansion and the consequent cooling down of the Universe, the equilibrium has broken and no new DM could be created, while the remaining can only annihilate. At a later stage of expansion, also the annihilation process stopped leading to the current "relic" DM, whose density  $\Omega_\chi h^2$  is measured with a value  $0.1148 \pm 0.0019$  by WMAP experiment [48] and  $0.1199 \pm 0.0027$  by the Planck collaboration [49]. Such results have the power of ruling out a large fraction of the SUSY parameter space, since they affect the gaugino mixing of the LSP. The consequent annihilation cross section must match the observed relic density of DM [49].

#### *Constraints from Flavour Physics*

Precision-measurements from flavour physics and observables in the electroweak sector of the SM constrains SUSY indirectly.

The measurement of the branching fraction of  $\mathbf{b} \rightarrow s\gamma$  [50] by the BABAR collaboration restricts indeed the off-diagonal mass matrix term for squarks.

The agreement of the  $B_s \rightarrow \mu^+\mu^-$  process with the SM measured by CMS and LHCb [51] seemed to completely rule out SUSY. Nonetheless, further studies proved that SUSY scenarios surviving the constraint set by the observed Higgs boson mass, are indeed compatible with the observation [52].

#### *Higgs Boson Discovery Impact*

The observation of a Higgs boson with a mass of 125 GeV is critical for SUSY as shown by the Equation (54). The requirement is loosened by radiative corrections to  $m_{h^0} < 135$  GeV, which makes the MSSM be in agreement with the observed mass of the Higgs boson. More constrained models not treated in this work, such as GSMB, reach a lighter value of the Higgs mass and are therefore ruled out in their current form [53].

In summary, it can be noticed that most of the constraints illustrated do not really rule out SUSY, which can rely on its vast number of parameters in order to be adjusted with the observations. The unique impacting measurement is then the Higgs boson observation, which implies that either most of the sparticles are in the range of 1-3 TeV or that the near-maximal mixing of the top quark occurs.



## Part II

### EXPERIMENT





## THE LARGE HADRON COLLIDER AT CERN AND THE ATLAS EXPERIMENT

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This chapter provides a brief description of the LHC accelerator complex regarding its construction, design and operations, and an overview of the ATLAS detector and its performance during operation of proton-proton collision runs from 2010 to 2016.

### 3.1 CERN AND THE LARGE HADRON COLLIDER

The Large Hadron Collider (LHC) [54, 55] is a circular proton-proton accelerator and collider situated at the Franco-Swiss border in the Geneva area and operated by the European Organisation for Nuclear Research (CERN<sup>1</sup>). The accelerator is hosted in a 27 km circular tunnel originally built in 1985 for its predecessor LEP [56], the Large Electron Position collider, which shut down in 2000. The tunnel is located approximately 100 m below the ground<sup>2</sup>.

The LHC is designed to accelerate beams of protons and perform proton-proton collisions at a centre-of-mass energy ( $\sqrt{s}$ ) of 14 TeV. Therefore, it results to be the most powerful particle accelerator ever built. The previously record holder, the Tevatron accelerator at Fermilab (USA), collided protons and antiprotons at  $\sqrt{s} = 1.96$  TeV until its closure in 2011.

The construction of the LHC took more than a decade between 1998 and 2008. However, an incident in the commissioning of the superconducting magnets in 2008 forced the accelerator to run at a lower centre-of-mass energy of 7 TeV for the first two years of operation between 2010-2011, followed by a period of run at 8 TeV in 2012 and eventually increased up to  $\sqrt{s} = 13$  TeV in 2015, after the first shut-down and upgrade period over the years 2013-2014.

The LHC is designed to accelerate not only protons but also heavy ions (Pb nuclei), which eventually can collide either with protons or with other heavy ions at an energy of 2.76 TeV per nucleon pair. However, this kind of physics studies are beyond the purpose of this thesis and they will not be discussed here.

#### 3.1.1 Experiments at the LHC

Along the circular accelerator ring there are four *interaction points*, as depicted in Figure 8. The beams running inside the LHC travel

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<sup>1</sup> acronym for the original french definition of "*Conseil Européen pour la Recherche Nucléaire*", which was the provisional agency prior the establishment of the current research organization.

<sup>2</sup> 170 m below ground near the Jura mountains and 45 m below ground on the side of Lac Léman

in opposite directions in separate pipes which have common sections only at these four points, around which four detectors have been built. The ATLAS (**A** Thoroidal LHC Apparatu**S**) [57] and CMS (**C**ompact **M**uon **S**olenoid) [58] are two *general-purpose* detectors located at opposite sides of the ring and they work at the accelerator design luminosity. At the other two interaction points there are two specialised experiments: the LHCb (LHC-**b**eauty) [59], which is dedicated to the study of **b**-physics and CP violation, and ALICE (**A** Large Ion Collider Experiment) [60], designed to investigate the properties of the quark-gluon plasma created in heavy ion collisions.

There are three smaller experiments located at the LHC: the LHCf [61] experiment consists in two imaging calorimeters each located 140 m away from ATLAS on both sides and it is designed for the study of neutral particles emitted in the very forward regions simulating cosmic ray showers at high energies; the MoEDAL [62] experiment is located in the LHCb cavern and is dedicated to searching for magnetic monopoles; TOTEM [63] experiment is used to study elastic scattering and the total proton-proton cross-section in the very forward physics of proton collisions.

### 3.1.2 *The Accelerator Complex and Design*

The LHC is a complex of several different accelerators built at CERN for the production of the proton beams, from the sample production to the final design energy and the collision. Figure 8 shows the scheme of the full accelerator complex.

#### *Sample production and acceleration*

Protons first originate from a source of ionized hydrogen atoms, after the electrons have been stripped off. Then, they are accelerated up to 50 MeV in the linear accelerator LINAC2, which has an Alvarez drift tube design, before being injected into the first circular accelerator, the BOOSTER. In the BOOSTER, the first bunches of proton are formed, squeezed and eventually accelerated to an energy of 1.4 GeV. Subsequently, the beam is injected in the Proton Synchrotron (PS), the oldest CERN accelerator, and accelerated up to 25 GeV. From the PS the protons are sent to the Super Proton Synchrotron (SPS) to be accelerated to 450 GeV, which is the injection energy of the LHC. Two transfer tunnels of 2.5 km length each connect the SPS with the LHC and allow the injection of two counter-rotating beams. There, it takes 20 minutes of further acceleration to reach the final energy.

Before entering the LHC, proton beams are ordered in bunches with a design value of about  $10^{11}$  protons per bunch and 2808 bunches per proton beam. The bunches are separated in time by 25 ns<sup>3</sup> and they are only few cm long and 16μm wide, leading to the possibility of multiple

<sup>3</sup> The bunch spacing of 25 ns is the design value. Between 2011-2012, a spacing of 50 ns was used for 1380 bunches per beam.

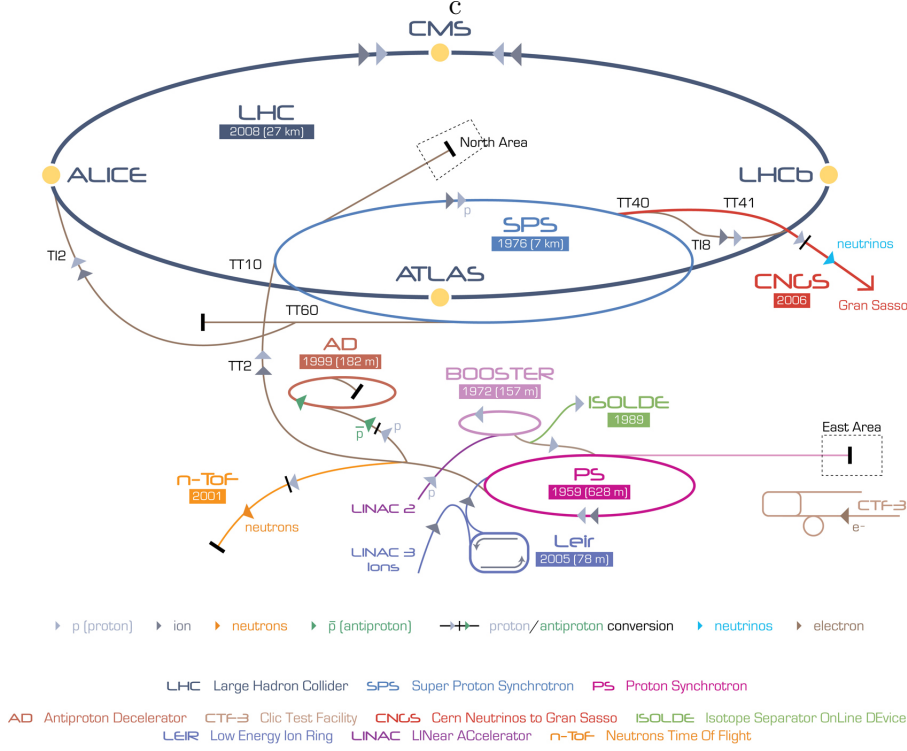


Figure 8: The LHC accelerator complex at CERN [64].

proton-proton interactions produced in the same bunch crossing, an effect also known as *pile-up* (see Section 3.1.3).

### 3.1.3 LHC Design and Luminosity

The orbital trajectory of the proton beams is kept as circular thanks to a system of 1232 Nb-Ti superconducting 14.3 m-long dipole magnets, providing a maximum magnetic field of 8.33 T. The magnets are cooled down to the working temperature of 1.9 K by liquid Helium which is below the phase transition from superfluid to normal. The beams of protons are focussed and defocussed by using 392 superconducting quadrupole magnets as lenses. A further set of sextupole and quadrupole magnets are used to keep the proton beams within the beam pipe due to the not-perfectly circular shape of the LHC.

While magnets are used to bend the trajectory of the proton beams, which are charged particles, the acceleration is achieved with a double Radio Frequency (RF) cavity system. Each beam has one cavity system composed by 8 cavities each with a 2 MV accelerating voltage oscillating at 400 MHz.

At the four points of interaction, proton-proton collisions take place. The produced number of events  $N$  for a given process with a cross section  $\sigma$  depends on the machine integrated luminosity  $L$ :

$$N = \sigma \times L \quad (56)$$

The integrated luminosity  $L$  can be expressed as  $\int \mathcal{L} \cdot dt$ , where  $\mathcal{L}$  is the *instantaneous* machine luminosity. The  $\mathcal{L}$  depends only on the beam parameters. For a Gaussian beam distribution, the instantaneous luminosity is given by:

$$\mathcal{L} = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (57)$$

where  $N_b$  is the number of particles per bunch,  $n_b$  the number of bunches in each beam,  $f_{\text{rev}}$  is the revolution frequency,  $\gamma_r$  the relativistic gamma factor,  $\epsilon_n$  the normalized transverse beam emittance,  $\beta^*$  the beta function at the interaction point and  $F$  a reduction factor to the geometric luminosity due to the crossing angle [54]. The term  $\epsilon_n \cdot \beta^*$  is a measure of the area of the beam spot at the interaction point.

### *Pile-Up*

Due to the high number of protons in each bunch, several proton collisions can happen at every crossing of the two bunches. The multiple proton collisions are known as *pile-up*. Pile-up is divided into two classes: *in-time* pile-up where the proton collisions recorded by the experiment come from the same bunch crossing, and *out-of-time* pile-up where proton collisions from the previous bunch crossings are interfering. The luminosity depends on the in-time pile-up and can be written in terms of the number of proton interactions per bunch crossing,  $\mu$ , leading to the following relation between  $\mu$  and  $\mathcal{L}$ :

$$\mu = \frac{\mathcal{L} \cdot \sigma_{\text{inel}}}{n_b \cdot f} \quad (58)$$

where  $\sigma_{\text{inel}}$  is the total inelastic proton-proton cross-section. As can be seen from the comparison between Figure 22 and 23, the mean number of interactions per bunch crossing  $\langle \mu \rangle$  increased from 9 to 24 from the beginning of Run1 to end of 2016 Run2, rising a serious challenge in addressing the pile-up *mitigation* problem.

#### 3.1.4 *LHC Performances*

The LHC design peak luminosity is  $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$ , a value reached for the first time in June 2016, almost 8 years after the accelerator start of operation. At the time of this writing, the current instantaneous luminosity record is  $2.09 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ , which is two order of magnitude greater than the value achieved by the Tevatron.

The LHC operations between 2010-2012 is called *Run1*. Collisions have been performed at  $\sqrt{s} = 7$  TeV, which is half of the design collision energy, up to 2011 and at 8 TeV up to 2012. In 2010, the total integrated luminosity delivered was  $48 \text{pb}^{-1}$ . Between operations in 2010 and 2011 the bunch spacing was decreased from 150 ns to 50 ns, and the number of bunches per beam as well as the number of protons per bunch were increased, resulting in an increase in the peak instantaneous luminosity as well as an increase in the  $\langle \mu \rangle$  value. In 2011, LHC delivered

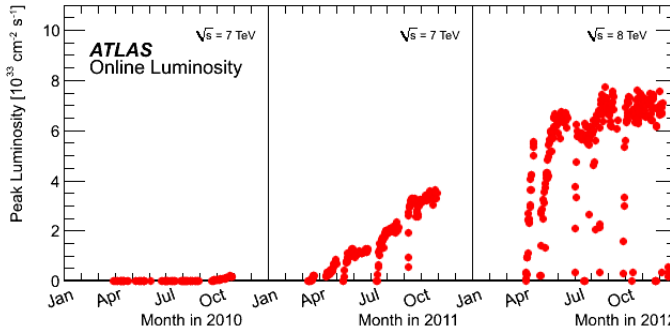


Figure 9: The peak instantaneous luminosity delivered to ATLAS per day versus time during the p-p runs of 2010, 2011 and 2012.

$5.46 \text{ fb}^{-1}$  of total integrated luminosity. In 2012 the collision energy was increased to  $\sqrt{s} = 8 \text{ TeV}$ . With the increase in number of bunches and beam intensity, the  $\langle \mu \rangle$  increased up to a value of 20.7, exceeding the design value of the LHC. The LHC delivered in 2012 a total integrated luminosity of  $22.8 \text{ fb}^{-1}$ .

After a two-years-long shutdown in 2013-2015, the accelerator came back to operations with an increased centre-of-mass energy of 13 TeV, only 1 TeV below its design value. The number of bunches was increased and the bunch spacing reached its design value of 25 ns, and LHC delivered in the years 2015-2016 - a run period called *Run2* - a total luminosity of  $38.5 \text{ fb}^{-1}$ .

Figure 9 and 10 show the increase in the instantaneous peak luminosity per day versus time during the runs in the Run1 (2010-2012) and in the Run2 (2015-2016), respectively.

### 3.2 THE ATLAS EXPERIMENT

ATLAS is a multi-purpose particle detector designed in a cylindrical shape around the interaction Point 1. Having a length of 40 m and radius of 25 m, for a total weight of approximately 7000 tonnes, it is the largest experiment at the LHC. Its design responds to both the LHC design parameters and the wide range of experimental signatures of the physics processes of interest: the search for a SM Higgs boson, the study of the electroweak symmetry-breaking mechanism, the precise measurements of properties of the Standard Model particles (in particular the Top quarks), as well as the search for direct evidence of new physics and other important processes.

The LHC physics goals and environment provide the following requirements on the ATLAS detector design [65, 66]:

- high-granularity in order to allow the separation of the large number of detected particles, reducing the impact of the *pile-up*, and for a good track reconstruction;

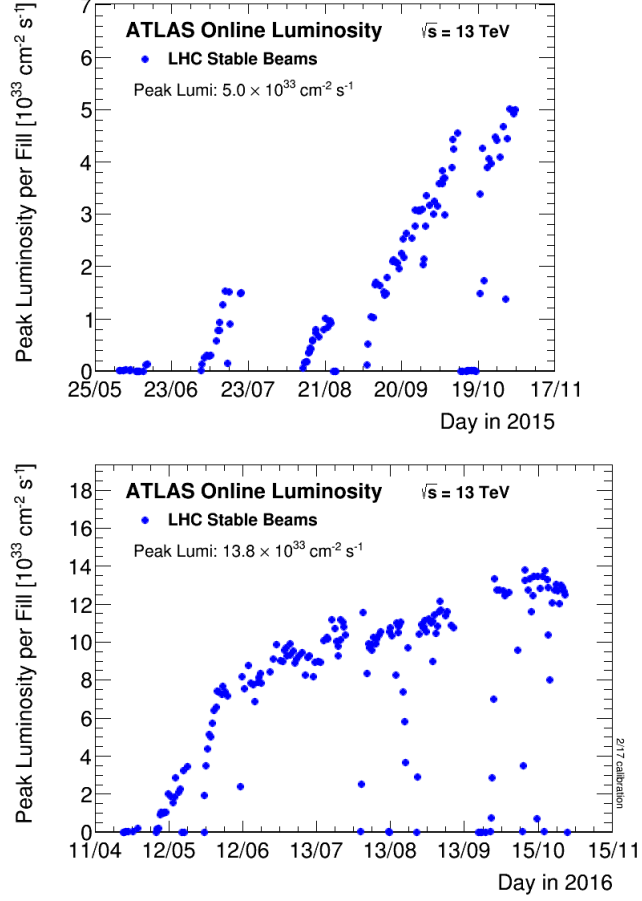


Figure 10: The peak instantaneous luminosity delivered to ATLAS for each LHC fill versus time during the p-p runs of 2015 (top) and 2016 (bottom).

- wide angular coverage in order to achieve a large acceptance of the particles emitted in different directions and to precisely reconstruct the missing energy from undetectable particles;
- very precise charged-particle tracking working at high *pile-up* conditions, with very high reconstruction efficiency, and heavy-flavour identification;
- excellent calorimetry system for electron/photon identification in the electromagnetic sector and for the jet and  $E_T^{\text{miss}}$  measurement in the EM and hadronic sector;
- high-precision identification of the muons and their momentum reconstruction.

The requirements on the various subsystems of the ATLAS detector are listed in Table 5. The design requirements include also the error on the impact parameters and the resolution of reconstructed vertices.

| Detector           | Resolution                                       | Coverage             |                      |
|--------------------|--------------------------------------------------|----------------------|----------------------|
|                    |                                                  | Measurement          | Trigger              |
| Tracking           | $\sigma_{p_T}/p_T = 0.05\% \cdot p_T \oplus 1\%$ | $ \eta  < 2.5$       | -                    |
| EM Calorimetry     | $\sigma_E/E = 10\% / \sqrt{E} \oplus 0.7\%$      | $ \eta  < 3.2$       | $ \eta  < 2.5$       |
| Had Calorimetry:   |                                                  |                      |                      |
| Barrel and End-cap | $\sigma_E/E = 50\% / \sqrt{E} \oplus 3\%$        | $ \eta  < 3.2$       | $ \eta  < 3.2$       |
| Forward            | $\sigma_E/E = 100\% / \sqrt{E} \oplus 10\%$      | $3.1 <  \eta  < 4.9$ | $3.1 <  \eta  < 4.9$ |
| Muon Spectrometer  | $\sigma_{p_T}/p_T = 10\%$ (for $p_T = 1$ TeV)    | $ \eta  < 2.7$       | $ \eta  < 2.4$       |

Table 5: Summary of the design resolution and coverage of the various ATLAS subsystems. Numbers are taken from [57].

### Coordinate System

The ATLAS detector is designed following a right-handed coordinate system where the  $x$ -axis is pointing towards the centre of the LHC ring and the  $y$ -axis is pointing upward, while the  $z$ -axis corresponds to the beam direction, with  $z > 0$  in the anti-clockwise direction. The interaction point is conventionally placed in the origin of the system - i.e. the centre of the detector - at the point  $x = 0$ ,  $y = 0$ ,  $z = 0$ . A cylindrical coordinate system can be defined by:

1.  $R = \sqrt{x^2 + y^2}$ , distance from the centre of the detector;
2.  $\phi \in [-\pi, \pi]$ , azimuthal angle measured with respect to the positive  $x$ -axis;
3.  $\theta \in [0, \pi]$ , the polar angle measured with respect to the positive  $z$ -axis (i.e. the beam);

The polar angle  $\theta$  is commonly re-expressed as the *pseudo-rapidity*:

$$\eta = -\ln \tan(\theta/2) \quad (59)$$

The advantage of such a definition is that differences in pseudo-rapidity are invariant under Lorentz boosts along the  $z$ -axis. The ATLAS detector can be split into two regions based on the pseudo-rapidity: the central "barrel" region corresponding to  $|\eta| < 1.4$  and the "end-cap" region at larger  $|\eta|$  values. With the pseudo-rapidity  $\eta$  is also possible to measure the angular separation between particles via the formula:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \quad (60)$$

Momenta and energies of the particles are usually described in the transverse plane ( $x, y$ ): the transverse energy  $E_T = E \cdot \sin\theta$ ; the transverse momentum  $p_T = p \cdot \sin\theta$ ; the missing transverse momentum  $E_T^{\text{miss}}$ , which measures the imbalance in the momentum in the transverse plane.

The transverse impact parameter of a trajectory of a particle  $d_0$  is defined as the shortest distance in the transverse plane between the trajectory and the beam axis.

The longitudinal impact parameter of a trajectory,  $z_0$  is defined as the  $z$ -position of the point of the trajectory closest to nominal beam axis ( $x = 0$  and  $y = 0$ ) or closest to the primary vertex, i. e. the position of the proton interaction with highest  $\sum p_T^{\text{tracks}}$ .

### 3.2.1 Detector Layout

As schematically shown in the cut-away Figure 11, the ATLAS detector is composed by a collection of several concentric sub-detectors, each sensitive to different types of particles produced in the collisions. The definition of the physical object as reconstructed from the detector response, such as leptons and jets, will be given in Chapter 5.

The detector can be described following its radial development from the interaction point (IP).

The *inner detector* (ID) [67, 68] sits closest to the IP and is composed of three tracking detectors: the Pixel Detector [69, 70], the Semiconductor Tracker (SCT) [71, 72, 73], and the Transition Radiation Tracker (TRT) [74, 75, 76]. The whole tracking system is enclosed in a 2 T magnetic field provided by the solenoid magnet [77], which bends the trajectory of the charged particles in order to allow the tracking system for the measurement of the transverse momentum of the particles.

Two calorimeters, the liquid argon electromagnetic calorimeters [78] and the Tile hadronic calorimeters [79], surround the ID. Together with the liquid argon hadronic end-cap calorimeters and the forward calorimeters, they constitute the calorimeter system dedicated to measure the energies of electrons, photons and hadrons as well as to reconstruct jets.

Finally, the *muon spectrometer* (MS) [80] is placed outside the calorimetric system, composed of muon chambers. It is employed to measure the trajectories of muons traveling outwards and it is housed inside a toroidal magnetic field [81, 82].

### 3.2.2 Magnet System

A particle carrying a  $q$  charge moving in a magnetic field  $\vec{B}$  with a velocity  $\vec{v}$  suffers a Lorentz force  $\vec{F} = q \cdot \vec{v} \times \vec{B}$ . Therefore, the trajectories of charged particles bend inside a magnetic field depending on the  $p_T$  of the particles, allowing the reconstruction of their momenta. As the energies reach values in the TeV range, strong magnetic fields are required. As shown in Figure 12, the magnet system used in ATLAS [83] consists of two parts: the solenoid magnet surrounding the inner tracking detectors, and the toroid magnet system integrated within the muon spectrometer. It makes use of *Nb-Ti* superconducting technology and is cooled down to 4.5 K. With a total size of 22 m in diameter and



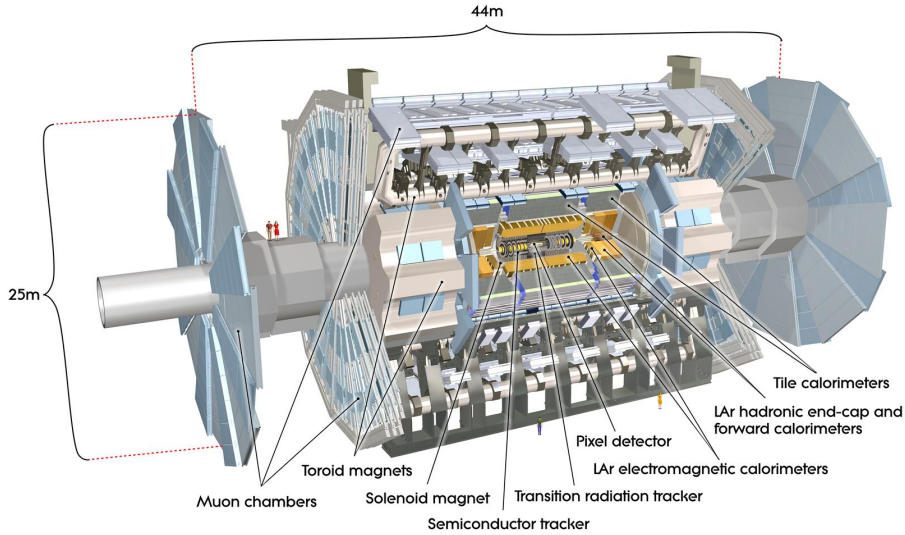


Figure 11: A cut-away view of the ATLAS detector, showing the different subsystems around the beam-axis. The main detector components are indicated.

26 m in length, it covers a volume of over  $12000 \text{ m}^3$  and stores around 1.5 GJ of energy.

#### *Solenoid System*

The central solenoid measures 5.8 m in length and a diameter of 2.5 m around the beamline. It provides a 2 T axial magnetic field in the inner detector, corresponding to a bending power of  $\langle BL \rangle \sim 2.3 \text{ T} \cdot \text{m}$ . To keep the amount of material before the calorimeters minimal, the solenoid has been designed to have only a thickness of two-thirds of the radiation length.<sup>4</sup> Therefore, besides providing measurement of the  $p_T$  of charged particles, it also ensures that the very low energy charged particles will bend-off and never reach the calorimeter.

#### *Toroidal System*

The toroid magnets are divided into a barrel toroid and two end-cap magnets at both sides of the interaction point. The barrel toroid has a total length of 25.3 m with inner and outer radii of 9.4 m and 20.1 m. It consists of eight coils that give atlas its characteristic shape, and provides a bending power of  $\langle BL \rangle \sim 3.2 \text{ T} \cdot \text{m}$ . Two end-cap toroids are inserted within the barrel toroid, each measuring 5 m in length with a bending power of  $\langle BL \rangle \sim 6.3 \text{ T} \cdot \text{m}$ . The toroids provide the muon system with a magnetic field of 0.5 T and 1 T in the barrel and end-caps respectively.

<sup>4</sup> A radiation length,  $X_0$ , is defined as the mean distance after which the energy of a particle is reduced by a factor  $1/e$  due to radiation losses only.

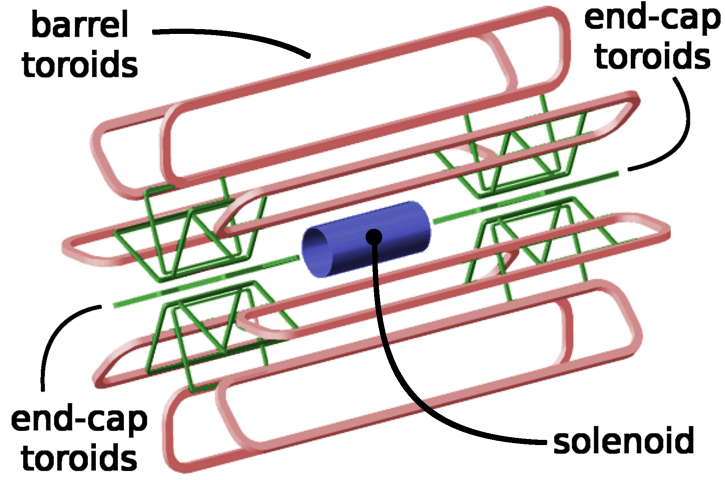


Figure 12: A schematic view of the ATLAS magnet systems.

### 3.2.3 Inner Detector

The inner detector (ID), depicted in Figure 13, is used for tracking and vertexing. It measures impact parameters at high resolution, provides a  $p_T$  measurement for charged particles with a resolution of 30% at  $p_T = 500$  GeV and allows for an efficient primary and secondary vertex reconstruction. It covers a pseudo-rapidity range of  $|\eta| \leq 2.5$ . The ID is 2.1 m in diameter and 6.2 m in length and is immersed in an axial magnetic field of 2 T.

The ID consists of three independent but complementary sub-detectors: the pixel detector, the semiconductor tracker, and finally the transition radiation tracker. In total, the ID provides a combined track momentum resolution of  $\frac{\sigma_{p_T}}{p_T} = 0.05\% \cdot p_T \oplus 1\%$ .

#### *Pixel Detector*

The pixel detector is the closest apparatus to the interaction point, built directly on the beryllium beam pipe. It is made of three concentric cylindrical layers in the barrel region located between 5 cm and 12 cm from the beam pipe, and two end-caps each of them consisting in three disks perpendicular to the beam direction at distances of 495 mm, 580 mm and 650 mm away from the interaction point at  $z = 0$ . The disks have an inner radius of 89 mm. The barrel layer closest to the beam, also called B-layer for its importance in secondary vertex reconstruction, is situated at a radius  $R_0 = 50.5$  mm. Each layer and disk supports 13 pixel modules, for a total number of  $80.4 \cdot 10^6$  pixels, each of them with nominal size of  $50 \times 400 \mu\text{m}^2$ . The modules are composed of silicon sensors bump-bonded to the front-end electronics and control circuitry. The resolution results to be  $\sigma_{R-\phi} = 10 \mu\text{m}$  in the radial direction and  $\sigma_Z = 115 \mu\text{m}$  in the  $z$ -direction. To suppress the electronic noise and protect the detector from radiation damage, a cooling system keeps the pixel detector at a temperature of 0 °C.

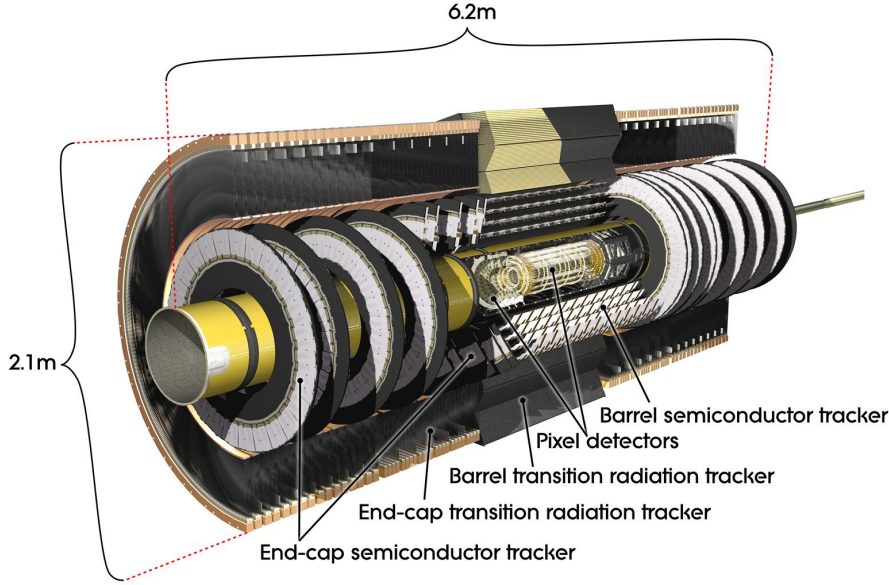


Figure 13: ATLAS inner detector.

#### *Insertable B-Layer*

The Insertable B-Layer (IBL) [84] has been installed closer to the beam-line during the first long-shutdown of the LHC between 2013 and 2015. It is a single-layer cylindrical pixel detector located between the beam pipe and the pixel detector at a distance of 3.3 cm from the interaction point. It allows for further improvements in vertex resolution, especially for the secondary vertices, which leads to improving the capability to identify jets originating from b-quarks. Moreover, the small distance to the interaction point improves the precision of the impact parameters,  $d_0$  and  $z_0$ . The IBL is build of a mix of silicon sensor technologies called *planar* and *3D*, which constitutes a new technology for the LHC experiments. The planar sensors cover most of the active area in the centre and are an incremental improvement of the existing Pixel detector. The 3D sensors are a new technology where electrodes pass through the sensor's bulk, allowing for lower bias voltages. The size of the pixels has also shrunk to  $50 \times 250 \mu\text{m}^2$ .

#### *Silicon Microstrip Detector*

The Semiconductor Tracker (SCT) is made using the silicon microstrip technology. It is composed of four layers covering the barrel region in the pseudorapidity range  $|\eta| < 1.4$  and two endcaps of nine disks each in the forward region  $1.4 < |\eta| < 2.5$ . The barrels have radii between 299 mm and 514 mm and a length of 1492 mm, while the disks are placed on each side at positions from 853.8 mm to 2720.2 mm and radii up to 56 cm. In total the SCT provides an active area of  $64 \text{ m}^2$  to measure four points over the full inner detector coverage with a total of 6.3 million of readout channels. The SCT has 4088 modules: 2112 rectangular modules in the

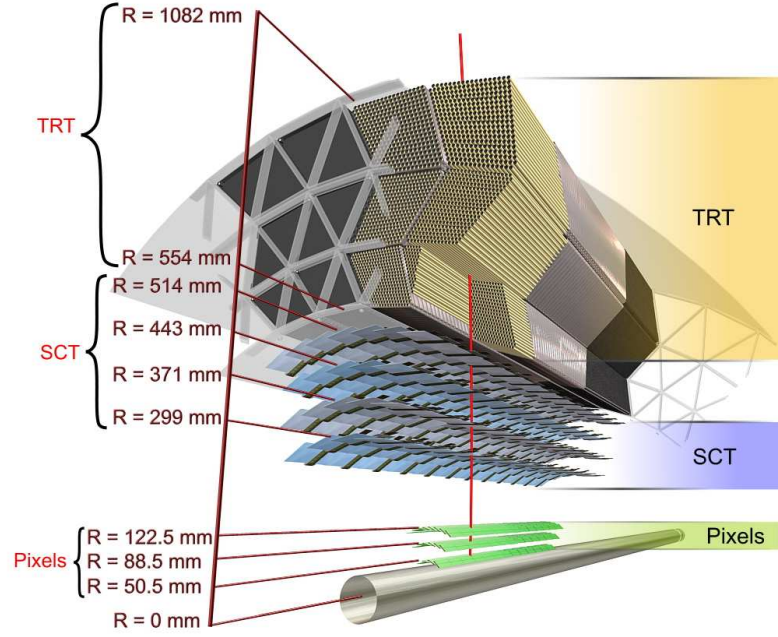


Figure 14: Transverse view of the ATLAS inner detector

barrel layers and 1976 wedge shaped modules of three different sizes in the endcap disks. To provide a measurement of the second coordinate the modules in the barrel layer are tilted with a 40 mrad stereo angle. In fact, the angle breaks the degeneracy along the  $z$ -direction and allows a resolution of  $17\mu\text{m}$  in the  $R-\phi$  plane and of  $580\mu\text{m}$  along the  $z$ -axis. Single-sided  $p$ - $in$ - $n$  silicon detector are used as sensors with an applied voltage of 150 V, potentially increasable in order to maintain an high charge collection efficiency. The SCT is cooled to the same temperature as the pixel detector.

#### *Transition Radiation Tracker*

The Transition Radiation Tracker (TRT) is a straw tube detector covering up to  $|\eta| < 2.0$  and forms the final part of the tracking system. It is based on the transition radiation emitted by a charged particle passing through two different dielectric materials, allowing the electron identification. It consists of 370,000 drift tubes, each 144 cm long and a 4 mm in diameter, filled with a gas mixture of 70% Xe, 27% CO<sub>2</sub> and 3% O<sub>2</sub>. Each tube contains a  $31\mu\text{m}$ -diameter gold-plated tungsten wire. A potential difference of  $-1.5\text{ kV}$  is set between the tube and the wire, so that the free electrons stripped-off by charged particles are drifted towards the wire, with a drift time proportional to the distance of the original particle to the wire.

By using material with different refractive indices in the polypropylene fibers (barrel) and the foils (end-caps), discrimination between electrons and hadrons can be achieved: the intensity of the transition radiation of a charged particle passing through different dielectrics is directly proportional to the  $\gamma$  Lorentz factor of the particle. The photons emit-

ted by transition radiation are absorbed by the Xe atoms in the gas, significantly amplifying the ionization signal. If two different thresholds for the TRT hits are applied, one optimised for direct ionisation detection and the other to detect transition radiation, electrons producing on average many more TRT photons compared to charged hadrons, such as pions, can be discriminated. The combined resolution is approximately  $50\text{ }\mu\text{m}$ . The TRT operates at room temperature.

#### 3.2.4 Calorimeters

Calorimeters are designed and used for the measurement of the energy of charged as well as neutral particles (electrons, photons, and hadronic jets), achieved by their total absorption, and the measurement of the shower properties, which also contribute to the particle identification. The depth of the calorimeter is crucial and must extend over many radiation lengths for electromagnetic interactions,  $X_0$ , or nuclear interaction lengths for strong interactions,  $\lambda^5$ .

The ATLAS calorimeter system surrounds the ID and is composed by two calorimeters: an electromagnetic calorimeter with a coverage of  $|\eta| < 3.2$  to detect electrons and photons, and a hadronic calorimeter covering the region  $|\eta| < 4.9$  to measure the energy of hadrons and hadronically decaying  $\tau$  leptons. Both calorimeters are of the *sampling* type: they consist of alternating layers of passive materials, inducing showering, and active materials to detect the secondary particles. Accurate spatial resolution is also required to precisely reconstruct the photons as well as for the missing transverse momentum calculation. Therefore, ATLAS calorimeter system is finely segmented in the longitudinal and azimuthal direction, allowing a fine reconstruction of the 3D shower position. Figure 15 shows a cut-away view of the calorimeter sub-systems.

##### *The Liquid Argon Electromagnetic Calorimeter*

The electromagnetic calorimeter (ECAL) is a liquid argon (LAr) [86] sampling calorimeter covering up to  $|\eta| < 3.2$ , essential in the electron and photon detection. It is divided into a barrel and an endcap region. Lead plates are used as absorbing material while liquid argon operates as the active material (due to its linear response function and its radiation hardness), extending over  $22 X_0$  in the barrel and more than  $24 X_0$  in the endcap to stop all electromagnetic showers. On the other hand, the material corresponds to only  $1.5 \lambda_s$ , in order to be as much transparent to hadronic object as possible. The *accordion-shaped* geometry of its design provides full azimuthal coverage, as shown in Figure 16. Measurements on the calorimeter energy resolution result in  $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E/\text{GeV}}} \oplus 0.7\%$ . Three copper layers work as readout electrodes in the gaps between the absorber material, where 2000 V voltage is

<sup>5</sup> The nuclear interaction length is the mean length traveled by hadron through matter before any interactions with the nuclei.



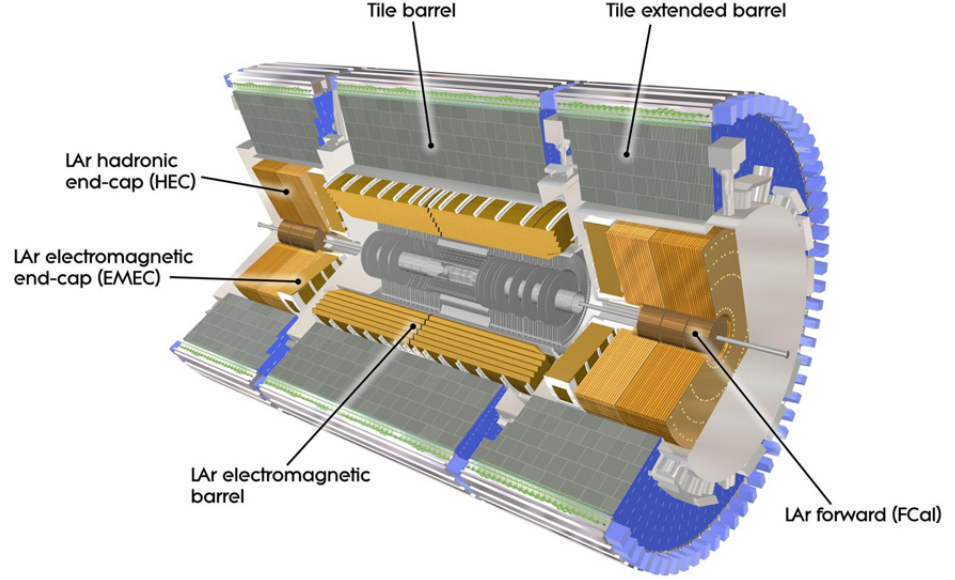


Figure 15: Schematic view of the ATLAS calorimeter system. Figure taken from [85].

applied to the outer layers. The inner plate is used as readout using capacitive coupling. Given the gap thickness and the drift velocities of the charges induced by ionisation, the drift time towards the electrodes is about 450 ns.

The barrel of the ECAL [87] covers  $|\eta| < 1.475$  and consists of two identical half-barrels with a gap at  $z = 0$ , housed in the same cryostat (shared with the central solenoid). In the barrels section with  $|\eta| < 2.5$  each module is segmented into three layers of rising granularity: the first layer, commonly referred as *strip*, with a granularity of  $\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$  allows a better discrimination between prompt  $\gamma$  and photons from  $\pi^0 \rightarrow \gamma\gamma$  decays; the second layer makes up most of the calorimeter with a  $16 X_0$  depth and contains most of a shower energy; the third layer measures the tails of highly EM showers and is used to distinguish electromagnetic from hadronic deposits, whose energy is released mostly at greater distances. The structure of an ECAL barrel module is shown in Figure 16.

The endcap calorimeters [88] consist of two coaxial wheels, inner and outer, with a radius of 0.33 m and 2.1 m respectively, one on each side of the barrels. The layout of the endcaps follows the barrel geometry. Three layers are placed in the region  $1.5 < |\eta| < 2.5$  including a strip layer, while only two layers of a coarser granularity are used in the outermost part of the outer wheel and the inner wheel.

Finally, the energy loss in the ECAL is measured through an additional 11 mm thin LAr presampler detector which is placed in front



ferent sampling layers and their granularity [57].

of the inner surface of the ECAL in the central region  $0 < |\eta| < 1.8$ . It provides a preliminary measurement before the first sampling layer, allowing a correction of the energy losses in material upstream the EM calorimeters.

## The Tile Hadronic Calorimeter

Surrounding the ECAL, the ATLAS hadronic calorimeter (HCAL) is used to measure the energy of the hadronic particles up to  $|\eta| < 3.2$ . The HCAL is composed of different independent sampling calorimeters, each with its own particular technology and choice of material. The choice was dictated by the different conditions in term of radiation flux and performance requirements needed as function of the particle pseudorapidity. The barrel section is segmented in three barrels, with an inner radius of 2.2 m and an outer radius of 4.25 m: the central barrel covers up to  $|\eta| < 1.0$  with a length of 5.8 m and two barrel extensions, each 2.6 m long, are placed covering the range  $0.8 < |\eta| < 1.7$ . In addition, two endcaps extend over  $1.5 < |\eta| < 3.2$ , as depicted in Figure 15.

The barrel sections are called the *Tile Calorimeter*, using steel layers with a thickness of 14 mm as absorber and plastic tiles with a thickness of 4 mm as detecting medium. At  $\eta = 0$  the calorimeter depth is  $9.7 \lambda$ . Both the central and the two extension barrels consist of 64 wedge-shaped azimuthal modules. A gap space of 60 cm is present between the central and the extended barrels, where ID service cables

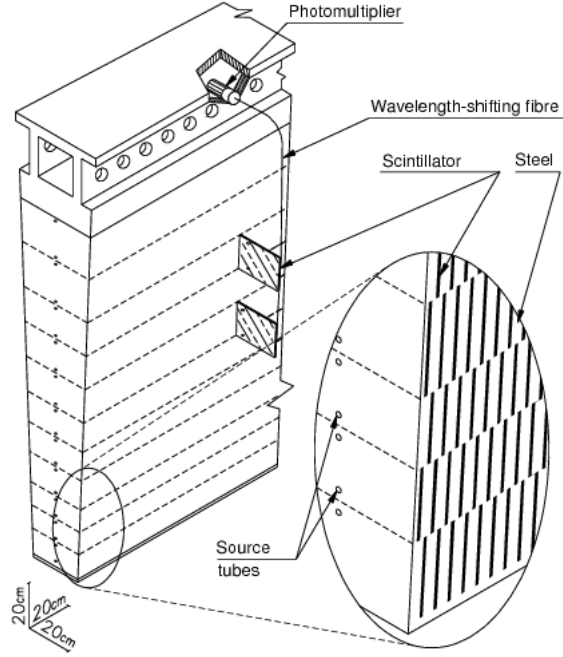


Figure 17: Schematic view of a tile calorimeter module, showing the alternating steel and scintillating material [57].

and LAr pipes are mounted, providing only limited instrumentation. The resulting scintillating light is read out by photomultiplier tubes at the tile edges, using wavelength shifting fibres. The whole structure is organised in periodic towers in  $z$  and  $\phi$  direction, as shown in Figure 17 while the grouping of fibres for the readout provides a coarse three-layer longitudinal segmentation.

The hadronic endcap calorimeter (HEC) is made of two disks per endcap, located directly behind its calorimetric counterpart. Each disk is made of 32 wedge-shaped modules of copper plates as absorbers and liquid argon as active material. The disks have a granularity of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  for  $1.5 < |\eta| < 2.5$  and  $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$  for  $2.5 < |\eta| < 3.2$ . The HEC is hosted in the same cryostat structure as the electromagnetic endcap and the forward calorimeters.

#### *Forward Calorimeter*

The final and most forward piece of the calorimeter system is the Forward Calorimeter (FCAL), a combined electromagnetic and hadronic calorimeter covering the region  $3.1 < |\eta| < 4.9$ <sup>6</sup>. It is built with rod absorbers embedded in a copper matrix. Between the two, a thin gap filled with liquid argon provides the active material. As the other calorimeters, the FCAL uses a layered design with 3 LAr based layers. The first layer uses copper as absorber material and is optimised for EM measurements, the second and third employ tungsten, predominantly

<sup>6</sup> corresponding to an approximate radius of 8 cm around the  $z$ -axis.



to absorb hadronic showers. The FCAL is approximately  $10 X_0$  deep. The granularity of the FCAL is coarser than the other calorimeters.

### *Resolution*

The typical energy resolution of the hadronic barrel and endcap calorimeters for hadronic jets is  $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E/\text{GeV}}} \oplus 3\%$  while for the FCAL the resolution is about  $\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E/\text{GeV}}} \oplus 10\%$ .

#### 3.2.5 *Muon Spectrometer*

The outermost and largest part of the ATLAS detector is the muon spectrometer (MS) [80], dedicated to the detection of the muons transversing the inner detector and both the calorimeters due to their long lifetime and low emission. It is designed to provide a precise measurement of the muon momentum from 3 GeV to approximately 1 TeV in the pseudorapidity range  $|\eta| < 2.7$ , with a design performance of stand-alone transverse momentum resolution of 10% for 1 TeV muons. Together with the inner detector, the MS is used to obtain both position and momentum measurements for muons. The MS has also the capability of reconstructing the muon track on its own, which is particularly important for fast event triggering as well as for the redundancy of the pattern recognition. In addition to the precise tracking, the MS also provides a muon trigger for the experiment for muons with  $|\eta| < 2.4$  using various  $p_T$  thresholds.

The MS is placed within the toroid magnets. It consists of a barrel region and end-cap regions with several wheels of detectors. Particularly, the outer large wheel gives the ATLAS detector its characteristic look. The conceptual layout of the muon spectrometer is shown in Figure 18: four different types of muons chambers are present for a total of 1 M ca readout channels.

### *Tracking*

Muon tracks are measured by two separate subdetectors, monitor drift tubes (MDT) and cathode strip chambers (CSC).

1150 MDTs are installed over the full coverage  $|\eta| < 2.7$  in the barrels and end-caps regions, positioned in the  $\phi$  direction. A typical MDT chamber consists of two multi-layers of drift tubes, separated by aluminium spacer bars. MTD chambers contain three to eight layers of drift tubes, depending on the position. Each of the tube consists of an aluminium pipe of 30 mm diameter with a tungsten-rhenium (W-Re) wire of 50  $\mu\text{m}$  running through the centre, filled with a gas mixture of 93% Ar, 7%  $\text{CO}_2$  at 3 bar. After the gas has been ionized by the passage of a muon, the electron avalanche is collected by the wires held at a voltage of 3080 V, allowing an electron drift time of 700 ns which is much larger than the bunch-spacing in nominal LHC conditions. MDTs are used to measure the coordinate only in the bending plane achieving

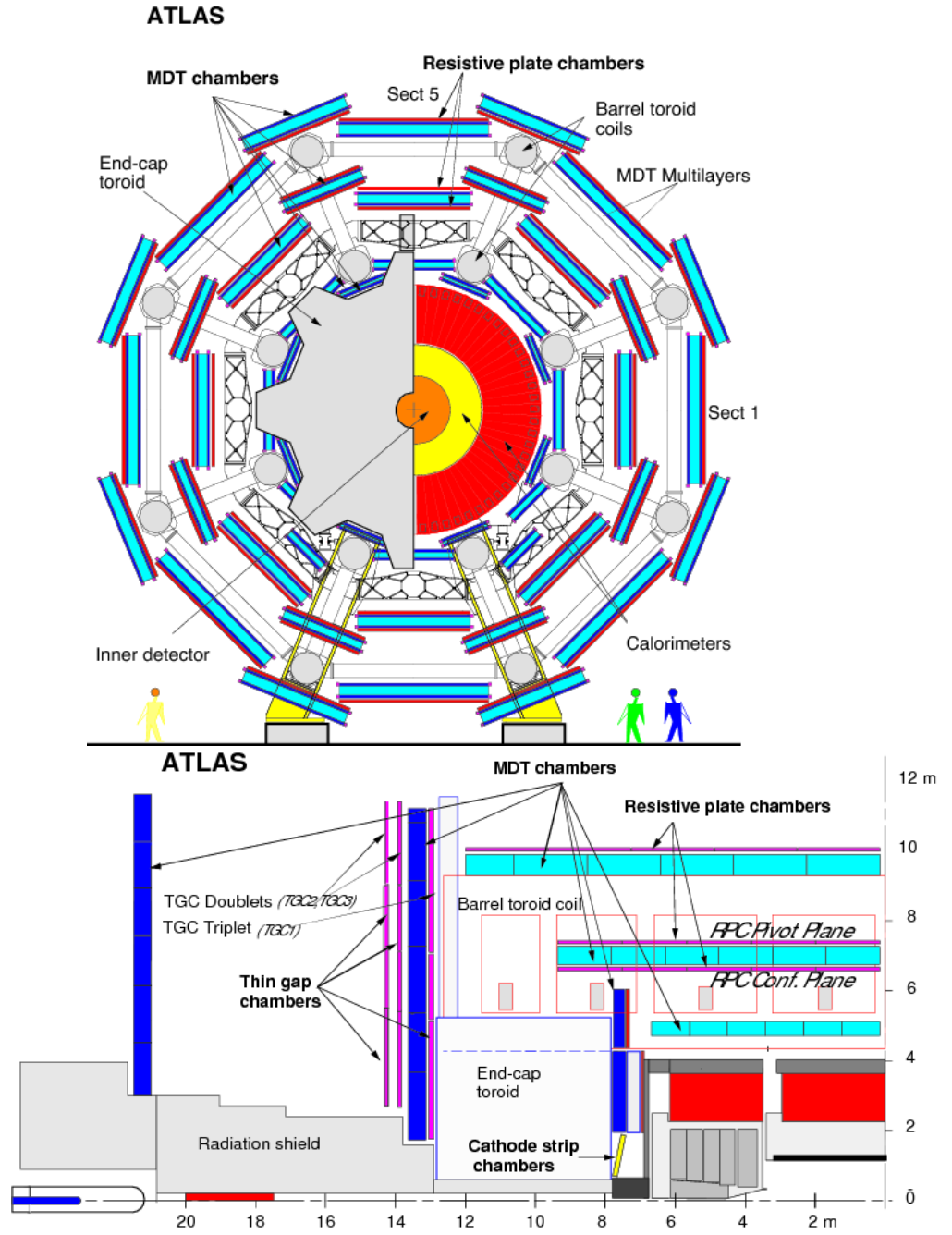


Figure 18: Schematic view of the muon spectrometer in the x-y and z-y projections, from [85].

an average in-situ resolution of 80  $\mu\text{m}$  per tube, depending on the drift time and 35  $\mu\text{m}$  per chamber. On average a muon is expected to leave a hit on 20 individual tubes.

The cathode strip chamber detectors are used in the most inner spectrometer layer, in the forward region  $2.0 < |\eta| < 2.7$ . The CSC are multi-wire proportional chambers filled with a gas mixture of 80% Ar and 20%  $\text{CO}_2$ . The cathodes are orthogonal splitted to provide a two-dimensional spatial resolution of the hits, allowing the charge distribution to be measured in both directions orthogonal to the beam axis. The maximum drift time for signal collection is 40 ns (compared to the 700 ns of the MDTs), thus providing higher acquisition rates as needed in the forward area. The spatial resolution is 40  $\mu\text{m}$  in the bending plane and about 5 mm in the transverse plane.

### *Trigger Chambers*

A second set of muon detectors are installed to be the muon triggering system and to complete the MDT measurement with a second muon position measurement. Resistive plate chambers (RPC) provide a trigger in the barrel region  $|\eta| < 1.05$  and consist of two parallel resistive plates separated by a 2 mm gap, where the gap is filled by a gas mixture of 94.7%  $\text{C}_2\text{H}_2\text{F}_4$ , 5% Iso- $\text{C}_4\text{H}_{10}$  and 0.3%  $\text{SF}_6$ . An electric field between the plates of about 4.9 kV/mm creates the electron avalanche when charged tracks traverse a chamber ionising the gas. The barrel region consists of three layers of modules of RPC with a resolution of 10 mm in both the z- and the transverse direction.

Thin-gap chambers (TGC) allow for triggering on forward muons. They are assembled in the end-cap wheels, covering the region  $1.05 < |\eta| < 2.7$  (2.4 for triggering). TCG are multi-wire proportional chambers similar to the CSC, but with the distance between the wires (1.4 mm) being shorter than between each wire and the anode (1.8 mm). This peculiar design ensures that the drift time is shorter than 25 ns, the design bunch spacing of the LHC, such that the bunch crossing responsible for firing the trigger can be identified with an efficiency higher than 99%. The gas mixture used is 55%  $\text{CO}_2$  and 45% n- $\text{C}_5\text{H}_{12}$ .

#### 3.2.6 *Forward Detectors*

The Zero-Degree Calorimeter (ZDC) is a quartz-tungsten calorimeter located at  $\pm 140$  m from the interaction point. It is designed to measure the centrality of heavy-ion collisions in ATLAS [89].

In the very forward regions of the ATLAS detector, three systems are designed to study the physics at very high pseudo-rapidities. Two of them are dedicated to measure the luminosity of the collisions in ATLAS: the Luminosity measurement using Cerenkov Integrating Detection (LUCID) and the Absolute Luminosity For ATLAS (ALFA) [90][91].

### *Luminosity Measurements*

The measurement of the integrated luminosity recorded by the detector is an essential input for the cross-section measurements and affects the background estimates and the sensitivity in searches for new physics.

The instantaneous luminosity  $\mathcal{L}$  for a  $p-p$  collider can be expressed by:

$$\mathcal{L} = \frac{\mu n_b f_{\text{rev}}}{\sigma_{\text{inel}}} \quad (61)$$

where  $f_{\text{rev}}$  is the revolution frequency,  $n_b$  the bunches colliding per revolution and  $\mu$  the average number of inelastic interactions per bunch crossing. The observed interaction rate per crossing measured during nominal data taking can then be used for the delivered luminosity measurement.

The LUCID detector consists of two components at each side of ATLAS, located at a position of  $z = \pm 17$  m, measuring the number of inelastic  $p-p$  interactions with 20 Cherenkov tubes. The count of the number of charged particles traversing the far forward region provides an online determination of the luminosity. The ALFA detector is located at position  $z = \pm 240$  m and consists of scintillating fibers installed in *roman pots* that can enter the beam pipe of the LHC and get as close as 1 mm to the beam. The scattering angles of about  $3 \mu\text{rad}$  are smaller than the nominal beam divergence and special runs with specific beam conditions are carried out for the ALFA measurements.

#### *3.2.7 Trigger and Data Acquisition*

The LHC operating at the nominal running conditions, with its design bunch spacing of 25 ns, has a collision rate of 40 MHz. Given an average ATLAS event size of 1.6 MB, the bandwidth needed to store all collision data amounts to  $\sim 65$  TB/s, which is far beyond the read-out and computing infrastructure possibilities. Moreover, only a small fraction of  $pp$  collisions results in events of interest for the subsequent data analysis, as the rate is dominated by low- $p_T$  inelastic and diffractive collisions. The trigger system is designed to filter out events passing specific eligibility request and consequently to reduce the amount of data to be read out, stored and reconstructed.

ATLAS uses currently a double-*level* trigger system to decrease the event rate to a final rate of approximately 1 kHz<sup>7</sup>. The two consecutive levels (L1 and HLT) select events based on certain criteria, which become more refined from level to level as the data rate gets reduced. A diagram of the process is illustrated in Figure 19. The current design results from the improvement of the original Run1 trigger system, which consisted in three levels. An upgraded version of L1 remained in Run2,

<sup>7</sup> The average final rate has been increased from the Run1 value of 400 Hz to 1 kHz for Run2 in order to deal with the new higher instantaneous luminosity.

while the former L2 and EF (Event Filter) have been merged into the more flexible HLT [92].

The selected events are subsequently stored on tape at the CERN computing centre (Tier0) where the final reconstruction takes place. The data is also replicated to sites all over the world where they can be processed and analysed using the Worldwide LHC Computing Grid [93, 94].

### *The L1 Trigger*

The Level-1 (L1) trigger [95] is an initial hardware-based trigger built on fast originally designed electronics and reduces the rate from 40 MHz to 100 kHz. It elaborates information from the energy deposits in the calorimeters (L1Calo)[96], from the hits in the trigger chambers in the muon spectrometer (L1Muon) and the minimum bias scintillators.

The L1Calo identifies local maxima of energy deposits in the calorimeters in ca 7000 *trigger towers*, regions with a coarse granularity of  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . These maxima are tested against predefined thresholds which are placed on the required energy for each object type. Electrons, taus, photons are identified from the different trigger objects<sup>8</sup> by the Cluster Processor (CP). The Jet/Energy-sum Processor (JEP) is responsible for using jet elements ( $2 \times 2$  trigger tower sums) to identify jets and calculate total and missing transverse energy  $E_T$  [97]. The trigger is able to decide in less than 2.5  $\mu$ s.

The L1Muon identifies high- $p_T$  muons coming from the interaction point using coincidence requirements between the different muon trigger chambers, by approximating the expected bending of the muon trajectory between muon stations

Information from the L1Calo and L1Muon trigger processors are combined and passed to the central trigger processor (CTP). The CTP holds a programmable look-up table defining up to 256 combinations of input signals to trigger an L1 accept. The L1 accept signal causes all the Read-Out Drivers (RODs) to send full detector data into the Read-Out System (ROS) buffers that feed the HLT. A prescale value  $p$  can be applied separately on each trigger item to accept only a fraction of the events that could pass a given trigger selection. Different prescales exist for L1 and HLT trigger levels.

During the shutdown of 2013-2015 between Run1 and Run2, the trigger system has been upgraded. Topological triggers at L1 (L1Topo) became available, which use combinations of kinematic information of both muon and calorimeter objects. This information can be used to trigger on high-mass di-jet events, targeting vector boson fusion, or di-muon events with a small di-muon opening angle coming from heavy flavour decays.

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<sup>8</sup> L1 electron and photon objects are defined as windows of  $2 \times 2$  EM calorimeter trigger towers. Trigger objects optimised for the identification of hadronic tau decays, make use of the same procedure while considering towers from EM and hadronic calorimeters.

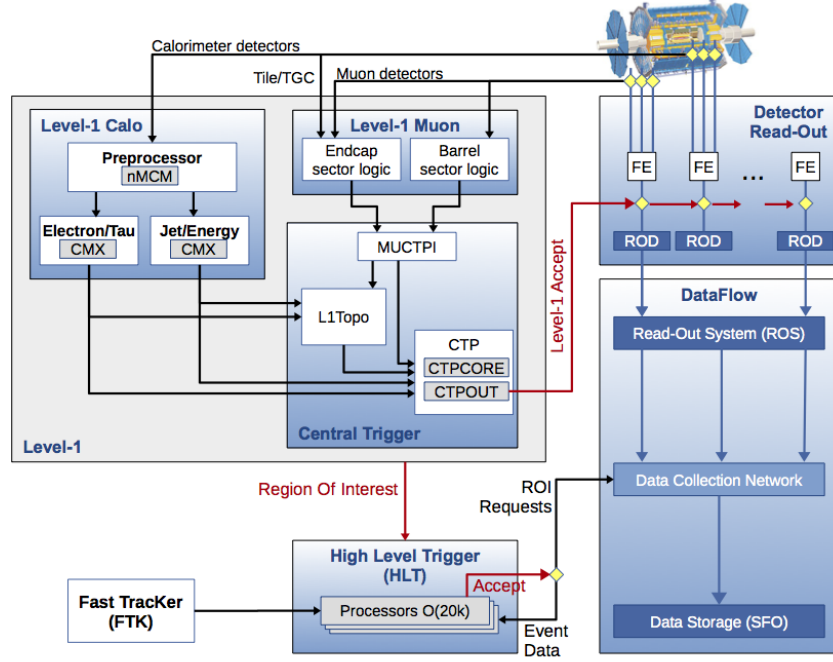


Figure 19: Block diagram of the ATLAS trigger/DAQ system in Run2. Figure taken from [98].

### The High Level Trigger

Events selected after the L1 trigger decision are passed to the high level trigger (HLT), a software-based trigger seeded by either the regions of interest defined at L1 or running particular reconstruction algorithms for specific detectors such as the calorimeters and the muon spectrometer. The HLT uses commercial computer servers running Scientific Linux CERN to perform offline-like event reconstruction and reduce the rate down from the Level-1 output rate of 100 kHz to the final value of 1 kHz on average within a processing time of about 200 ms. The output of the HLT is then saved to disk.

The HLT decisions differs from the L1 in flexibility, thanks to the lower input rate and the available full detector information. The decisions are organized into trigger chains and use the information about calibrated object multiplicity and advanced photon/electron/b-jet identification.

Electrons are selected at the HLT using a likelihood-based identification criteria taking as input EM shower shape and tracking information with different selections available. Muons are reconstructed at the HLT by combining the inner detector and muon spectrometer tracks. Tau candidates are identified at the HLT using a boosted decision tree (BDT) built from calorimeter and track quantities using different working points. HLT jets are formed from topological energy clusters at the EM scale, then they are calibrated to the hadronic scale by first applying a jet-by-jet area subtraction procedure followed by a jet energy scale weighting that is dependent on the HLT jet  $p_T$  and  $\eta$  [99].

### *The Fast TracKer*

The Fast TracKer (FTK) [100] project is a fast hardware-based tracking system designed to perform a global track reconstruction receiving input from the ATLAS silicon tracking detectors after each Level-1 trigger. It will provide full-event track information to the HLT. This can be used to improve many trigger selections requiring full-event tracking information, like b-jets, which would not be otherwise affordable at HLT. In addition the precise estimation of the pile-up conditions per event can be used to develop pile-up robust trigger strategies. With the Run-2 data taking ongoing, the first boards of FTK are being installed, already reading ATLAS data in parasitic mode. The full deployment and operation of the barrel region is expected for 2017, after which the integration within HLT and the extension to full coverage will follow[99].

### 3.2.8 *Data Quality and Performances of the ATLAS Experiment*

Following the LHC accelerator timeline described in Section 3.1.3, the ATLAS data acquisition program has been in operation from 2010 to 2016 (at the time of this writing), with a mid-term shutdown during 2013-2014 dividing the data taking into two periods, *Run1* (2010-2012) and *Run2* 2015-2016. The ATLAS detector data taking efficiency, i.e. the ratio of the ATLAS recorded luminosity over the total LHC delivered luminosity, has been outstandingly always above 90% since the start of data-taking. Figure 20 and 21 show the cumulative luminosity recorded by ATLAS in the Run1 (2011-2012) and Run2 (2015-2016), respectively. Moreover, the ATLAS detector showed such an impressive capability of data taking despite the increasing complexity of the recorded events due to the already cited *pile-up* effect, whose distribution can be seen in Run1 and Run2 in Figure 22 and 23, respectively.

ATLAS data taking is organised in *Runs*, a period defined by the start and stop of the data acquisition system. Each run is subdivided into luminosity *blocks*, the smallest data unit within ATLAS. Each block holds a comparable amount of data, so that its duration is luminosity-dependent. All detector subsystems permanently monitor their functionality during data taking. Besides automated online systems, dedicated data quality shifters check the data quality run by run, to ensure that no faulty detector behaviour affects the performance of the experiment. Small defects, like noisy calorimeter cells for instance, are masked before the bulk reconstruction of runs. Larger defects, like offline subsystems, are recorded in a data quality database along with the affected luminosity blocks. This database is used later to create so-called *Good Run Lists*, a collection of run and luminosity blocks which can be used for physics analyses. Masked blocks are simply rejected in the analysis and the total luminosity is calculated based on blocks passing the criteria. A summary of the beam parameters, and luminosities in the four years of ATLAS operation is given in Table 6.

| Beam Parameters                                                 | 2010  | 2011 | 2012 | 2015 | 2016 |
|-----------------------------------------------------------------|-------|------|------|------|------|
| Centre-of-mass energy $\sqrt{s}$ [TeV]                          | 7     | 7    | 8    | 13   | 13   |
| Peak luminosity [ $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ]        | 0.21  | 3.65 | 7.73 | 5.02 | 13.8 |
| Integrated delivered $\mathcal{L}[\text{fb}^{-1}\text{y}^{-1}]$ | 0.048 | 5.46 | 22.8 | 4.2  | 38.2 |
| Integrated recorded $\mathcal{L}[\text{fb}^{-1}\text{y}^{-1}]$  | 0.045 | 5.08 | 21.3 | 3.9  | 35.6 |
| Minimum bunch spacing [ns]                                      | 150   | 50   | 50   | 25   | 25   |
| Average pile-up $\langle \mu \rangle$                           | 3     | 9.1  | 20.7 | 13.7 | 24.2 |

Table 6: Summary of the run conditions during the  $\text{p} - \text{p}$  data taking from 2011 to 2016. Values from operation in the years 2010 to 2016 are taken from [101]



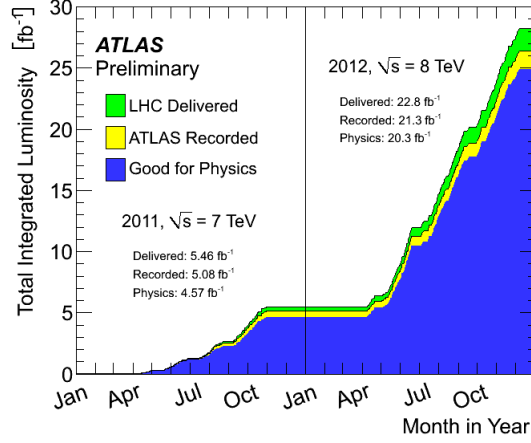


Figure 20: Cumulative luminosity versus time delivered by LHC (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) for the pp collisions at 7-8 TeV centre-of-mass energy in 2011-2012.

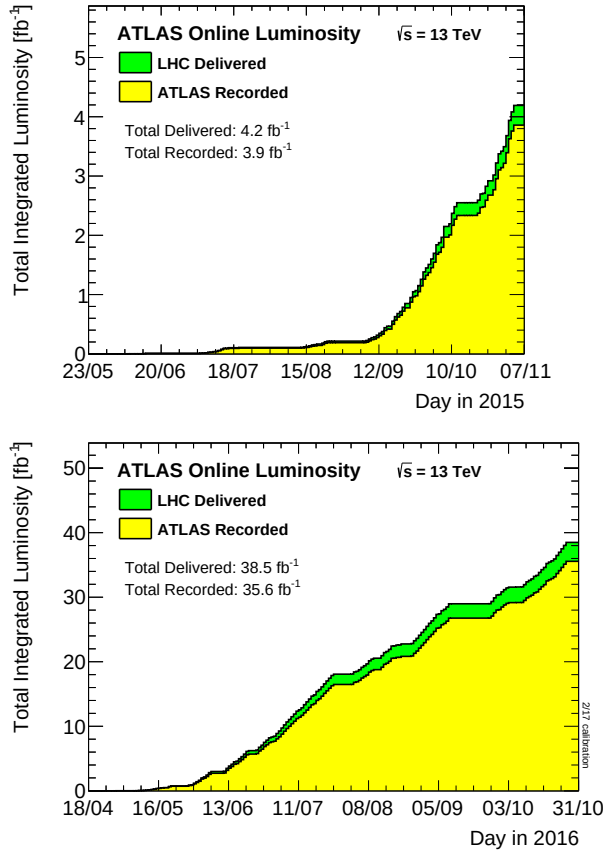


Figure 21: Cumulative luminosity versus time delivered to (green) and recorded by ATLAS (yellow) during stable beams and for the pp collisions at 13 TeV centre-of-mass energy in 2015 (top) and 2016 (bottom).

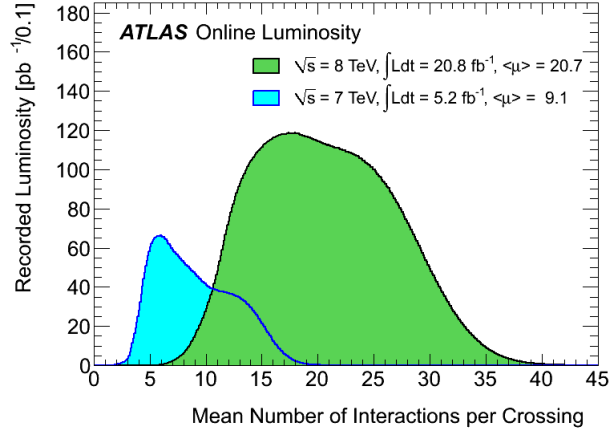


Figure 22: Luminosity-weighted distribution of the mean number of interactions per bunch crossing  $\langle \mu \rangle$  for the 2011 and 2012 data.

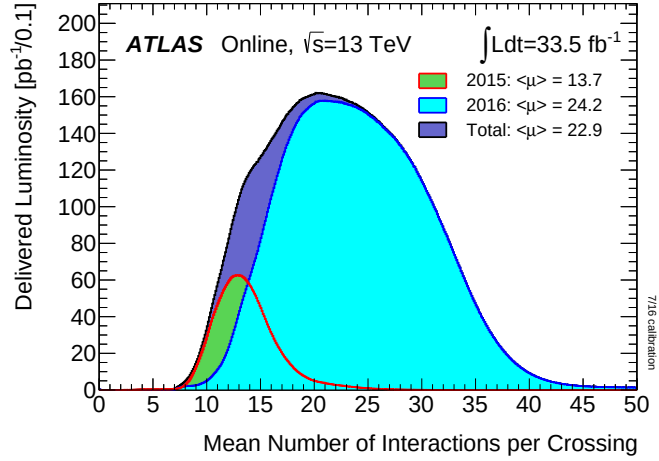


Figure 23: Luminosity-weighted distribution of the mean number of interactions per bunch crossing  $\langle \mu \rangle$  for the 2015 and 2016 data.

In any scientific experiment, the observation must be compared to the expected results in order to obtain any conclusion. The good understanding of the expected measurement, including its errors, is fundamental. Therefore, accurate simulation of physics processes and the interaction of the emerging particles with the detector material is crucial for a fair comparison with the observed data in order to model the expected contribution from background or signal sources.

Simulated datasets are obtained in different steps: Monte Carlo (MC) event generators simulate the SM (or BSM) processes produced in the  $pp$  collisions at the LHC collider by using pseudo-random numbers to create individual events reproducing on average the predicted distributions. Then, MC techniques are used to simulate the detector response to the interaction with the particles. Finally, simulated events are reconstructed in the same kind as the measured ones.

In this section, a review of the calculation techniques and phenomenological models used for prediction at hadron colliders is presented, along with an overview of the MC generators used in ATLAS, and specifically in this analysis. In addition, a description of the ATLAS detector simulation is given.

#### 4.1 SIMULATION OF $pp$ COLLISIONS

Events are generated from the initial proton-proton collision, whose simulation requires description of physics processes at different energy scales: from the high-energy scale of the deep inelastic scattering between the partons to the soft regime of the hadronisation process, which can not be described in terms of perturbative QCD, making a full analytic description not possible.

However, a factorisation of the  $pp$  collisions simulation into steps at different energy scales, as depicted in Figure 24, is possible: the hard scatter between the proton constituents, the showering of partons, hadronisation and the underlying events all can be simulated. The factorisation allows the perturbative computation of cross sections for processes with hadrons in the initial state. Therefore, the simulation of the hard interaction can be computed up to a fixed order in perturbation theory, while phenomenological models can be used to describe the softer scales.

##### 4.1.1 *Factorisation Theorem*

The basic property that enables the perturbative computation of cross sections for processes with hadrons in the initial state is their factori-

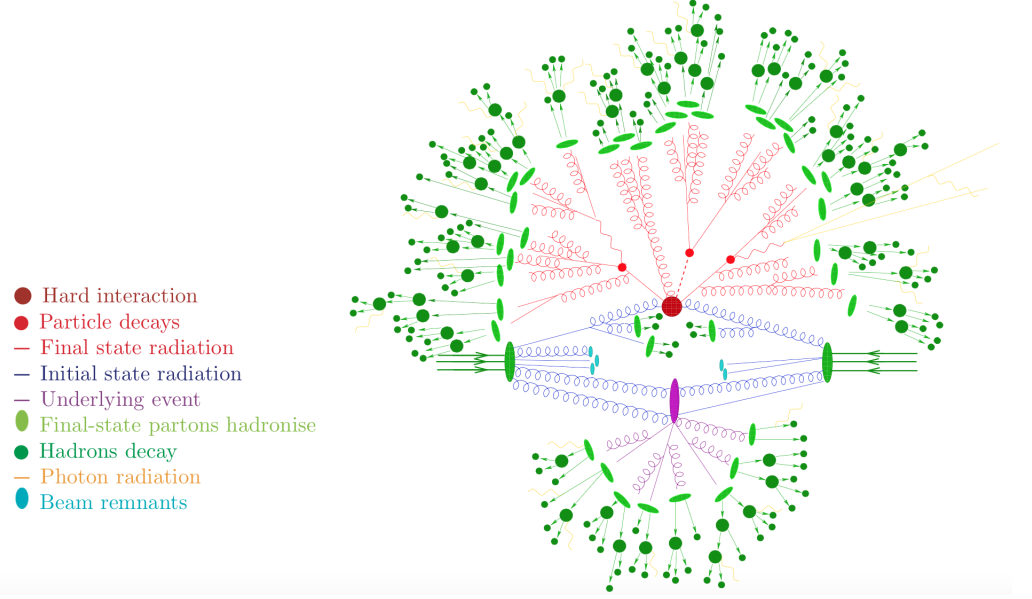


Figure 24: Schematic illustration of a  $t\bar{t}H$  event produced in a proton-proton collision. The hard interaction (big red blob) is followed by the decay of both top quarks and the Higgs boson (small red blobs). Additional hard QCD radiation is produced (red) and a secondary interaction takes place (purple blob) before the final-state partons hadronise (light green blobs) and hadrons decay (dark green blobs). Photon radiation occurs at any stage (yellow). Figure from [102].

sation into a process-dependent hard scattering happening at short distances and a process-independent long distance component, the parton distribution functions (PDFs), absorbing the non-perturbative physics.

The factorisation theorem [103] allows then to obtain the overall cross section for the production of any final state  $X$  in the collision of two hadrons by convoluting the hard scattering cross section  $\hat{\sigma}_{ab \rightarrow X}$  with the PDF  $f(x, Q^2)$  via the formula:

$$\sigma_{AB \rightarrow X} = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \hat{\sigma}_{ab \rightarrow X} \quad (62)$$

where the sum runs over the parton types that can initiate the process and  $x_a$  and  $x_b$  are the fraction of the total momentum carried by the partons  $a$  and  $b$ . The value of  $Q^2$  is usually chosen to be equal to  $\mu_F$ , that is the factorisation scale introduced to separate the soft from the hard distance physics. The choice of factorisation scale is arbitrary, by including an infinite number of terms in the perturbative series. For a given order  $N$  of the series, the residual uncertainty of  $O(\alpha_S^N + 1)$  is used to account the arbitrariness of  $\mu_F$ .

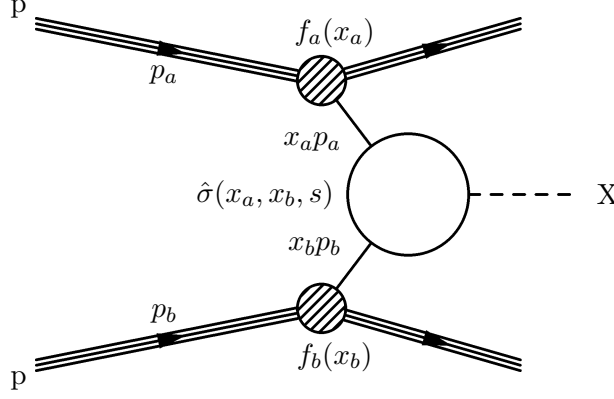


Figure 25: Diagram of a generic hard scattering process. The partons, extracted from the colliding pp pair, carry a momentum fraction with respect to the proton energy described by a parton distribution function.

#### 4.1.2 Parton Distribution Function

The PDFs describe the composition of the proton in terms of partons. It gives the probability of finding a parton carrying a fraction  $x$  of the proton momentum at a given scale  $Q^2$ . The dependency of the PDF on  $Q^2$  can be obtained through the DGLAP<sup>1</sup> equations [104, 105, 106]. The evolution of the PDF  $f_q(x, Q^2)$  for a quark  $q$  is then:

$$\frac{d}{d \log Q^2} f_q(x, Q^2) = \frac{\alpha_s}{2\pi} \int_x^1 \frac{d\xi}{\xi} f_q(\xi, Q^2) P_{qq'}\left(\frac{x}{\xi}, \alpha_s\right) \quad (63)$$

where the kernels  $P_{qq'}$  are the Altarelli-Parisi *splitting functions* [107]. At LO they can be interpreted as the probability for a parton  $q$  to be originated by a parton  $q'$  carrying momentum  $\xi$  larger than  $x$ . The splitting functions can be computed perturbatively as a power series expansion in  $\alpha_s$ .

The dependency of the PDF on  $x$  cannot be computed with perturbative QCD calculations but they are determined experimentally by globally fitting the PDF dependent predictions for different processes and different ranges of  $x$  and  $Q^2$  to the measured datasets, while constraining the parameters (typically from 10 to 30) of the functional form.

There is a big variety of PDF-sets available provided by several collaborations. They differ mainly in the choice of data from different experiments, the functional form used in the parametrisation, the value of  $\alpha_s$  used and other parameters. H1 and Zeus experiments at HERA used the analysis of  $e^-p$  scattering to provide inputs for the PDF calculation [108]. The most commonly used PDF-sets at the LHC are MSTW [109], NNPDF [110], and the CTEQ [111]. Figure 26 shows the PDFs from the NNPDF results: it can be seen that for protons, at

<sup>1</sup> Dokshitzer-Gribov-Lipatov-Altarelli-Parisi

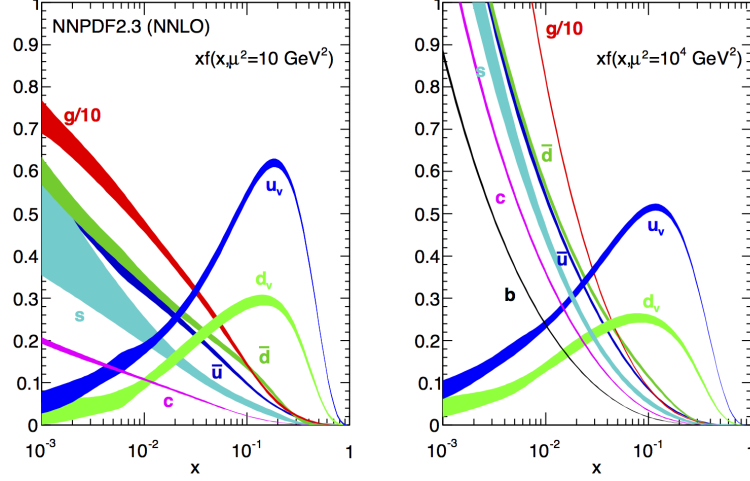


Figure 26: Parton distribution functions at two different resolutions scales,  $10 \text{ GeV}^2$  (left) and  $10^4 \text{ GeV}^2$  (right). This set of parton distribution functions are provided by the NNPDF collaboration [110].

small  $Q^2$  and large  $x$  values the  $u$  quarks are the dominant distributions, while at small  $x$  the gluon density dominates over the vanishing valence quarks. All densities decrease at large  $x$  and the shape of gluon distributions rise strongly with increasing  $Q^2$ .

#### 4.1.3 Hard Scattering: Matrix Elements

The cross section calculation for partonic process is also referred to as Matrix Element (ME) calculation, because it involves the calculation of the scattering matrix relating the particles in the initial and final state of the process.

The cross section for the hard scattering between two partons  $\hat{\sigma}_{ab \rightarrow X}$ , as illustrated in Figure 25, can be computed explicitly at a fixed order (LO, NLO, etc.) in perturbative QCD. This introduces a dependence on a renormalisation scale  $\mu_R$ .

Matrix elements are calculated perturbatively and the calculation for the hard-scattering is typically done at leading order. The partonic cross section for a  $2 \rightarrow n$  process at LO can be given by:

$$d\sigma_{\text{LO}} = \frac{1}{2\hat{s}} \int d\Phi_n |M_{\text{LO}}(\Phi_n, \mu_F, \mu_R)|^2 \quad (64)$$

where  $d\Phi_n$  is the  $n$ -particle phase space and  $M_{\text{LO}}$  the squared matrix element (ME) for the process considered.

NLO generators are used to compute infrared and collinear safe observables at one loop. NLO calculations includes diagrams contributing to a certain process till a fixed order in  $\alpha_S$ , allowing to decrease the dependance on the scale choice and providing more reliable estimates of the normalisation and shape of distributions, as it accounts for extra

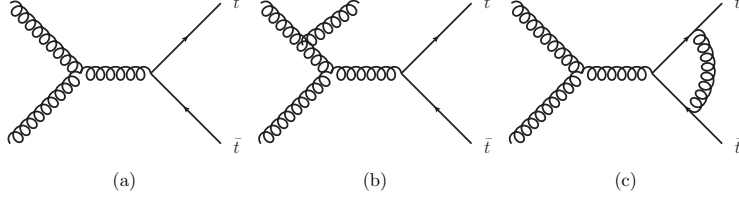


Figure 27: Example Feynman diagrams of  $t\bar{t}$  production for (a) leading order, (b) first real emission and (c) first virtual correction.

radiation. A calculation of a  $2 \rightarrow n$  process at NLO, as represented in the diagrams in Figure 27, is composed by three components:

$$\sigma_{\text{NLO}} = \int_n \sigma^{\text{B}} + \int_n \sigma^{\text{V}} + \int_n \sigma^{\text{R}} \quad (65)$$

where  $\sigma^{\text{B}}$  is the Born level term,  $\sigma^{\text{V}}$  the virtual correction and  $\sigma^{\text{R}}$  considers the contributions of diagrams with the real emission, consequently with  $n+1$  particles in the final state. Next-to-leading log (NLL) *resummation* techniques are also employed in the calculation of the cross-sections, in order to contrast the only partial cancellation of real and virtual divergences for some observables, when additional logarithms of the form  $L = \ln(Q^2/Q_0^2)$  appear for each order in  $\alpha_s$ .

#### 4.1.4 Parton Showers

The cross section of the hard interaction from the proton-proton collisions can be evaluated with the factorisation theorem, so that the ME for parton emission factorises and each parton in the event can be treated as branching independently of other partons. The partons usually carry a large momentum and they can produce a shower of secondary partons with lower momenta through gluon splitting ( $g \rightarrow q\bar{q}, g \rightarrow gg$ ) or gluon emission ( $q \rightarrow gq$ ). The emission or radiation during the evolution of the parton shower by final state partons is the *final state radiation*, while the emission from the upcoming partons is called *initial state radiation*.

The parton shower (PS) generators use MC techniques to simulate successive emissions from the partons in initial or final state via a succession of  $1 \rightarrow 2$  branchings. This event generation step provides an approximate estimation for high parton multiplicity states and for higher-order corrections, in particular in the phase space where the emissions are soft or collinear. The evolution of the parton shower is described using the same DGLAP splitting functions described in Equation 63. The  $n+1$  parton differential cross section is then calculated from the  $n$ -parton cross section as:

$$d\sigma_{n+1} \approx d\sigma_n dP_i(z, Q^2) \approx d\sigma_n \frac{\alpha_s}{2\pi} \frac{dQ^2}{Q^2} P_{ji}(z) dz \frac{\Delta_i(Q_1^2, Q_2^2)}{\Delta_i(Q_2^2, Q_0^2)} \quad (66)$$

where  $dP_i(z, Q^2)$  is the probability that parton  $i$  will split into two partons with parton  $j$  carrying a fraction  $z$  of the momentum of parton  $i$ . The simulation algorithm proceeds iteratively on each parton from the hard interaction. The implementation of the parton shower in this calculation is done via the Sudakov form factors [112], which represents the probability of a parton evolving from the scale  $Q_1^2$  to a lower value  $Q_2^2$  with no emission of a gluon with energy larger than a given value:

$$\Delta_S(Q_1^2, Q_2^2) = \exp \left\{ - \int_{Q_2^2}^{Q_1^2} \int_{z_{\min}}^{z_{\max}} dP_i(z, Q^2) \right\} \quad (67)$$

The evolution continues until it reaches a cutoff value  $Q_0^2$ , when the parton can not emit any other resolvable partons and hadronisation begins. The calculation can be adapted for both the case of initial and final state radiations.

#### 4.1.5 Matrix Element and Parton Shower Matching

Fixed-order calculation of ME as represented in Equation 64 can be done at LO or expanded to higher order to achieve a better accurate description of the final state, although with an infrared cut-off to prevent divergences from soft and collinear emissions. In this case, parton shower addition provides a complementary description of the event structure, but a double counting of certain phase space regions is possible. Matching and merging techniques provide a consistent combination between the ME fixed-order description at high momentum-transfer scales and a parton-shower one at low scales.

The procedure to distinguish between hard and large-angle emissions, described by the ME, and soft and collinear emissions, described by the PS, is referred to as ME-PS matching. Several variants of LO matching exist, the most widely-used matching schemes are the Catani-Krauss-Kuhn-Webber (CKKM) [113, 114, 115, 116] and Michelangelo L. Mangano (MLM) [117, 118] algorithms. They are now the standard approach for the simulation of multi-jet final states for LHC analyses.

#### 4.1.6 Underlying Events

Besides the hard scattering, soft interactions may happen among spectator partons from the colliding protons. These processes are referred to as *underlying event* (UE) [119]. The UE activity is due to different contributions. First, the beam-beam remnants, that are the left-overs of initial hadrons after the parton hard scattering. Then, multiple gluon scatterings per proton collision are likely to occur because of the large cross section for gluon-gluon scattering, so that the generic soft scattering of partons is referred to as multiple partons interactions (MPI). The low energy scale of those processes requires the use of several non- or semi-perturbative phenomenological models whose parameters in the MC generators are tuned based on the experimental results [120].



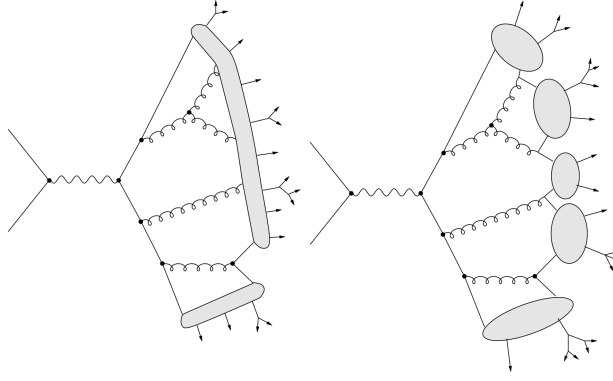


Figure 28: Sketch of the radiation pattern generated by a  $q\bar{q}$  pair and the following hadronisation models of (left) string fragmentation and (right) cluster hadronisation. Figure from [121].

#### 4.1.7 Hadronisation

The evolution of the parton showering and the underlying events stops when the energy of the emitted partons decreases down to the hadronisation scale  $Q^2 \approx 1$  GeV, which is identical by construction to the infrared cut-off of the parton shower. At this energy scale, the confining effects of QCD become important and the dynamic of the system enters a non-perturbative phase where observed color-neutral hadrons are eventually formed in the final-states. This transition process is referred as to hadronisation or jet-fragmentation.

Event generators rely on QCD-inspired phenomenological models to describe the hadronisation process. The most used models are the *string* and the *cluster* models.

##### The Cluster Model

The cluster model [122] is based on the concept of the preconfinement property of QCD [123], for which the quarks and gluons produced in the showering step are organized in color-singlet clusters of partons with a invariant mass distribution at low scales. The model relies on forcing the final state gluons to split in not-perturbative way into  $q\bar{q}$  pairs and then grouping partons to form colorless clusters. The technique is illustrated in the right picture of Figure 28. The original clusters momentum is given by the momentum sum of the constituents. The clusters with higher masses will split into smaller ones, while the low masses clusters undergo isotropical decay into pairs of hadrons, using weights depending on the phase space. The decay is simulated with 3-body decay models with intermediate resonances.

##### The String Model

The string model [124] is based on the property of linear confinement [125]. In non-perturbative QCD, the potential of a color-dipole field grows linearly with the separation of the charges and more and more energy is

stored in a stretched string connecting them, as depicted in the left picture of Figure 28. For a  $q\bar{q}$  pair, as the color charges move apart, when the energy becomes of the order of hadron masses, it becomes energetically favorable for the string to break and create a new  $q\bar{q}$  pair. The two segments of string will stretch and break again, until all the energy has been converted into quark-antiquark pairs connected by short strings.

## 4.2 MONTE CARLO GENERATORS

There are many Monte Carlo generators used for the simulation of the different physics process of interest. They can generally be classified as either *general purpose* or *matrix element* (ME) generators. The general purpose generators are capable to perform the entire proton collision simulation chain, while ME generators simulate only the hard-scattering and have to be interfaced with an additional parton shower generator.

### 4.2.1 General Purpose MC Generators

General purpose generators simulate the entire proton collision from the hard scattering matrix element, which is typically calculated at LO, and including the parton shower and hadronisation steps. Those generators are limited to  $2 \rightarrow 1$  and  $2 \rightarrow 2$  processes and any extra particles are due to parton showering.

- PYTHIA [126, 127] is a multi-purpose generator where the hard scattering is calculated at LO, then QCD and QED radiations are added in shower approximation with the best accuracy when the emission angle of the shower particles is small. It can also be interfaced with the output of ME generators. The Lund string model [128] is used for hadronisation. In the UE simulation MPI events are included.
- HERWIG [129, 130] is an other multi-purpose generator that can be interfaced with a different generator simulating the hard-scattering step. The difference lies in the implementation of the following steps. The hadronisation is done with the cluster model.
- SHERPA [102] is a MC generator capable to provide NLO hard scattering calculations and match them with its own parton shower algorithm based on the Catani-Seymour dipole formalism [131, 49]. It provides a better description in case of high multiplicity of jets than other generators. SHERPA version 2.2.1 and 2.1.1. is used to model the  $W/Z/\gamma + \text{jets}$  and  $WW/WZ/ZZ$  backgrounds for the analysis here discussed.

### 4.2.2 Matrix Element Generators

Matrix element generators simulate only the hard scattering at LO and NLO and rely on interfaces with other general purpose generators for

the parton showering process.  $2 \rightarrow n$  processes can be included so that a specified number of initial/final state radiation particles can be included at ME level instead of simulated through parton showering.

- MG5\_AMC@NLO [132] is the evolution of the previous ME generator MADGRAPH5 [133] with an alternative on the interface between an NLO calculation and the showering. The procedure allows to maintain the NLO precision in the matching, in order to avoid double counting which possibly appears if the hard emissions is matched with the soft/collinear emissions without a proper scale, as they are handled by two different generators. It is used for the simulation of the SUSY signals, interfaced with PYTHIA8 for analysis here discussed.
- POWHEG [134] is an event generator computing ME at NLO in perturbative QCD. Unlike MC@NLO, POWHEG produces events with positive (constant) weight, and, furthermore, does not depend on the Monte Carlo program used for subsequent showering. It can be interfaced with any other MC generator. POWHEG-BOX [135] is a framework that implements the whole procedure concerning an NLO process. It is used for the simulation of the  $t\bar{t}$  and single-top processes for analysis here discussed.

### 4.3 ATLAS DETECTOR SIMULATION

After the simulation of the hard scattering, the showering and the decay of the intermediate unstable particles, the output of the MC generators is a list of 4-vectors of all the stable particles produced in the event. This format can be used to study the physics processes at *particle level*, also called *truth level* as the complete informations about the particle decay chain is available and each object is reconstructed directly from the simulated process.

In order to compare the simulation results with the recorded data, the MC has to be analysed after the reconstruction in the detector, i.e. at the reconstruction level. An accurate simulation of the apparatus allows also detailed studies of the detector response and efficiencies. The ATLAS collaboration developed a detector simulation performed by GEANT4 [136, 137] framework. The simulation models the interaction of the particles with the detector and produces an output equivalent and comparable to the data collected by the ATLAS detector starting from the event generated as described before. Consequently, the same triggers and reconstruction algorithms applied on data can be used on the simulated samples.

The detailed description of the interaction of the particles with the various regions of the detector is performed and the detector response as particles interact with its matter is simulated as hits in the sub-detector systems of ATLAS. In the *digitisation* step, energy deposits are converted into electronic signals taking into account the geometry, materials and readout system of the ATLAS detector. The digitisation

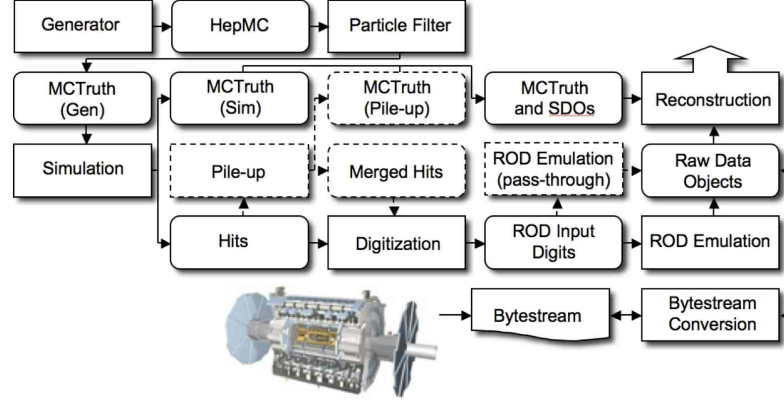


Figure 29: The flow of the ATLAS detector simulation software, from MC event generators (top left) to the Raw objects given as input for the reconstruction algorithms (top right) [136].

output is a Raw Data Object that can be directly passed through the reconstruction algorithms which apply the same calibrations as used for measured events. Figure 29 shows the ATLAS detector simulation flow with the different steps of the MC and data processing.

The precise simulation of the full detector is highly demanding in terms of amount of CPU time, primarily due to the slow simulation of the calorimeter processes. The detector simulation is by far the dominant cause of ATLAS CPU usage and computing resource availability is currently on the edge. The *fast simulation* software program, known as ATLFAST-II or AFII, reduces considerably the CPU time necessary to process the events by trading simulation accuracy with speed. A parameterized description of the particle showers in the calorimeters is applied [138] while significantly reducing the computational time of simulating particles going through the detector. The full granularity of the calorimeter is therefore not used. The AFII simulation is used in the generation of SUSY events used in the analysis described in this thesis.

## OBJECT RECONSTRUCTION AND PARTICLE IDENTIFICATION

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The ATLAS detector is designed such that traversing particles will result from the distinctive trace left by the particle interaction with the different subsystems of the detector, as shown in Figure 30, with the exception of the neutrinos that interact only via weak force leaving no trace in the system.

After the detector response, the next step is attributing the information collected to real physical objects. The data passing the online trigger requirements are in a format called *Raw*. Raw data, as well as simulated events, are further reprocessed, then calibrated to account for any differences between data and simulation, and reconstructed to a format suitable for performing physics analysis.

This chapter provides a description of the reconstruction and identification of the main physics objects relevant for the analysis presented, as well as the performances of the used algorithms. The methods employed to estimate efficiencies and the calibration of these objects are reviewed and their uncertainties are also briefly discussed. All algorithms are implemented in the software framework ATHENA [139].

The description of the reconstruction algorithms focuses on the methods used for the data collected during the 2015 and 2016 Run2 and successively selected and analysed.

### 5.1 TRACKING AND VERTEXING

Charged particles traversing ATLAS leave hits in the inner detector which are then combined into tracks, one of the most important physics objects for particle reconstruction and identification. Moreover, the reconstruction of the vertex, i.e. the point which the tracks originate from, is important to identify where either the  $p - p$  interaction took place (*primary vertex*) or the decay of a long lived particle produced in the collision happened (*secondary* or *displaced vertex*). Furthermore, a precise measurement of the track impact parameter allows the identification of heavy-flavour quarks inside the jets.

#### 5.1.1 Track Reconstruction

Tracks are reconstructed from hits in the inner detector by a sequence of algorithms [141, 142]. Tracks within the full ID acceptance of  $|\eta| < 2.5$ , with a  $p_T > 400$  MeV are considered for track reconstruction. There are two different approaches used to reconstruct the tracks:

- **Inside-out** algorithm is the baseline track reconstruction procedure. It uses hits in the Pixel and SCT detectors as seed for track

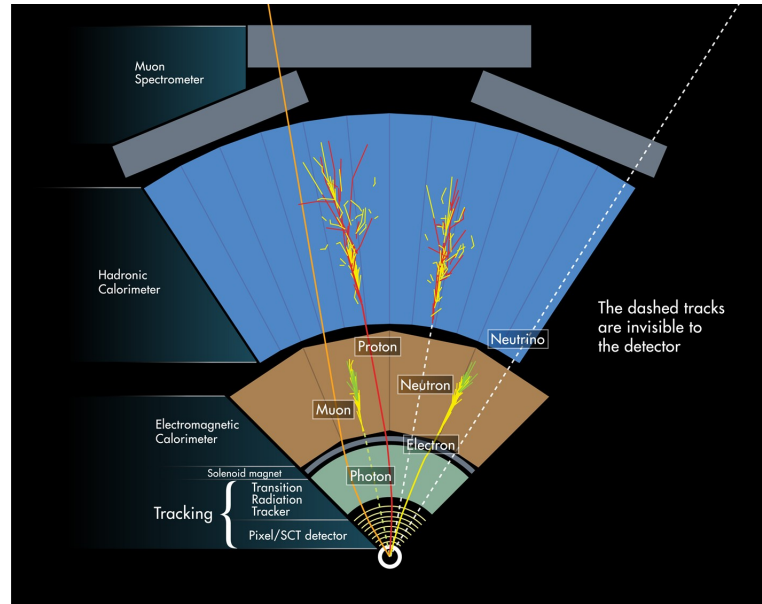


Figure 30: Schematic representation of the detector components in a plane perpendicular to the LHC beam line (transverse plane) in the barrel region. Only a small sector of the azimuthally symmetric detector is shown, starting outwards from the LHC beam pipe. The scheme shows the typical signatures for various particles as measured in the different detector layers, where solid lines represent directly measurable trajectories of charged particles, and dashed lines the straight trajectories of neutral particles with no direct signals in the trackers. Figure from [140].

candidates, adding the hits by moving away from the interaction point using a combinatorial Kalman filter [143]. More than one track candidate can be formed from the same seed.

- **Outside-in** algorithm starts with hits in the TRT as the seed for the track candidate and extend them towards the inner layers of the detector by adding silicon hits. Back-tracking is used to reconstruct secondary particles, i.e. particles coming from the decay of primary particles and recover secondary tracks from conversions, material interactions and long-lived particle decays.

The same space point can be assigned to more than one track candidate and ambiguities on candidates must be resolved to remove fake tracks. To minimise the selection of fake tracks, a set of quality criteria is set by assigning tracks a score depending on their quality, where the score is based on the number of *hits*, *holes* and *outliers* found. Holes are space points where a hit is expected, but not observed. Outliers are space points assigned to the track candidate which result in a poor track fit. Both holes and outliers reduce the score. If two track candidates share a hit, then it is assigned to the track candidate with the highest score. The scores of the two track candidates are then recalculated and other ambiguities will be resolved until no more remain.

For every reconstructed track, the impact parameters  $d_0$  and  $z_0$  are calculated as the closest distance between the track and the primary vertex at the point of closest approach in the transverse plane, in the transverse ( $d_0$ ) and in the longitudinal ( $z_0$ ) planes.

The track reconstruction efficiency is defined as the fraction of primary particles matched to a reconstructed track. The accuracy of the reconstruction of charged particle trajectories is limited by the combined effect of the finite resolution of the detector elements, the knowledge of the locations of the detector elements, of the magnetic field, and of the amount of material in the detector. The reconstruction is also affected by the occupancy of detector modules, particularly in dense environments resulting from jets at high pile-up. For tracks with  $p_T > 400$  GeV the efficiency, derived in a MC sample of non-diffractive events, approaches 90%. The track reconstruction efficiency as a function of  $p_T$  of the track can be seen in Figure 31.

Misalignments of the active detector elements deteriorate the resolution of the reconstructed track, while correlated geometrical distortions can lead to systematic biases on the reconstructed track parameters [145]. The ID has been aligned using a track-based technique [146] which minimizes the track-to-hit residuals by correcting the alignment parameters. It allows the alignment of all tracking subsystems together, with the position of each individual module known to a precision better than  $1\mu\text{m}$  [145].

### 5.1.2 Vertex Reconstruction

After the track reconstruction, their origin has to be determined from the hard-scattering processes. This information is crucial for physics

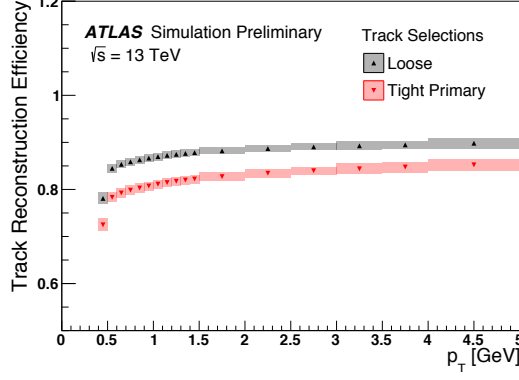


Figure 31: Track reconstruction efficiency, evaluated by using minimum bias simulated events, as a function of truth  $p_T$ . The bands indicate the total systematic uncertainty. The Figure is taken from [144]

analyses, especially at high pile-up conditions, as it improves the knowledge on the number of additional interaction from pile-up. The preselection on tracks for the vertex reconstruction requires 4 hits in the SCT, 9 hits in total in the silicon trackers (pixel and SCT) but no holes in the pixel detector. In addition, at least 1 hit in the IBL or the first layer of the pixel detector and no more than 1 hole in the SCT. They must also have  $p_T > 400$  MeV,  $d_0 < 4$  mm and a resolution of the impact parameters of  $\sigma(d_0) < 5$  mm and  $\sigma(z_0) < 10$  mm.

Primary vertices, i. e. vertices corresponding to  $p-p$  interactions, are later reconstructed using a *finding-through-fitting* procedure [147, 142]. The algorithm proceeds as follows:

1. A set of tracks are defined passing the previously described requirements.
2. Vertex seeds are found from the global maximum in the distribution of the  $z$ -position at the beamline of the reconstructed tracks.
3. The vertex position is determined using an adaptive vertex  $\chi^2$  fit.
4. Once the position of the vertex is determined, the tracks displaced by more than  $7\sigma$  are discarded and used to seed a new vertex.
5. The reconstruction is performed again with the remaining tracks of the event.

More than one vertex is generally found per event. The vertex with the largest sum of squared transverse momenta of the associated tracks ( $\sum p_T^2$ ) is then chosen as primary vertex of the event, while others are denoted as pile-up vertices.

The vertex reconstruction efficiency in data can be calculated by taking the ratio between events with a reconstructed vertex and events with at least two reconstructed tracks. The measured vertex efficiency in a subset of data at  $\sqrt{s} = 13$  TeV is shown in Figure 32, compared with simulation events.



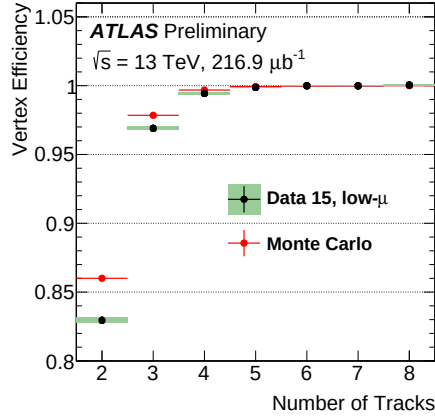


Figure 32: Efficiency of vertex reconstruction as a function of the number of tracks in the low- $\mu$  data. The Figure is taken from [148].

## 5.2 JETS

Many of the processes in the proton-proton collisions contain quarks and gluons in the final state. As they fly-off in different directions, colour confinement causes them to fragment and hadronise into a collimated spray of particles. A collection of hadrons originating from a quark or a gluon or single hadrons, as pions, coming from decays of unstable particles form showers in the calorimeter which are commonly referred as *jets*. The highly segmented design of the ATLAS calorimeters enables the reconstruction of jets with high precision. The jet energy left in the calorimeters is measured so that jets are used as a proxy for the original partons produced in the collision, as they have roughly the same energy and direction as the original parton.

### 5.2.1 Topological Clustering

The jets are reconstructed using clustering techniques [149, 150]. The algorithm starts considering 3-dimensional clusters of energy deposits in the calorimeter. Firstly, *seed* calorimeter cells having a signal-to-noise ratio (cell-signal significance) above a predefined threshold  $t_{\text{seed}}$  are selected. Then, the clusters are formed by grouping topologically connected neighbouring calorimeter cells (*topo-clusters*) with a signal-to-noise ratio above a low threshold  $t_{\text{neighbour}}$ . The cell-signal significance is defined as the cell-energy deposit divided by the average expected noise as input:

$$\Gamma_i = \frac{E_i}{\sigma_i} \quad (68)$$

where  $\sigma_i$  is a noise level of cell  $i$ , defined as the sum in quadrature of electronic and pile-up noise. In the third step, an extra layer of cells with  $\Gamma > t_{\text{cell}}$  on the perimeter of the clustered cells are added. The choice of the threshold values  $\{t_{\text{seed}}, t_{\text{neighbour}}, t_{\text{cell}}\}$  gives also name to

the clusters such that EM clusters are "633" and hadronic clusters are "420" clusters. This analysis uses specifically jets built from topo-clusters at the electromagnetic(EM) energy scale. After topo-clusters are found, a splitting algorithm further separates the resulting clusters based on local energy maxima.

### 5.2.2 Jets Reconstruction and Calibration

Jets can be identified from the clusters using a jet finding algorithm. Such algorithms should satisfy certain robustness criteria, i.e. to be safe against additional infrared and collinear radiation of additional partons, so that the emission of soft or collinear gluons should not affect the definition of the reconstructed jets; be invariant under z-axis boost transformations; be less dependent of the underlying event and other non-perturbative effects<sup>1</sup>.

#### Reconstruction

The algorithm used in ATLAS is the Anti- $k_t$  algorithm [151], which is both infrared and collinear safe. The algorithm combines clusters hierarchically based on the distance between two objects  $i$  and  $j$ ,  $d_{ij}$ , and between an object and the beam,  $d_{iB}$ , defined as:

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{r^2} \quad (69)$$

$$d_{iB} = p_{T,i}^{2p} \quad (70)$$

where  $\Delta R_{ij}^2$  is the geometrical distance between the objects  $i$  and  $j$ ;  $r$  and  $p$  are algorithm parameter and  $r$  defines the size of the jet, typically with a chosen value of 0.4 or 1.0. If  $d_{ij} < d_{iB}$ , the 4-vectors of the  $i$  and  $j$  clusters are combined and the algorithm calculates the next minimum distances. Otherwise, if  $d_{ij} > d_{iB}$ , the cluster  $i$  is considered a "jet" and removed from the cluster list and the minimal distances are recalculated. The algorithm runs until there are no clusters left and all jets in the event have been identified. In the Anti- $k_t$  algorithm, the parameter  $p$  is set to -1, to ensure that objects with large  $p_{T,i}$  tend to combine with soft objects and the jet becomes infra-red collinear safe, otherwise a soft-soft object combination would lead to fake energetic jets.

In order to reduce the number of jets coming from pile-up, information about the tracks associated to the jet are used. In Run1, the Jet Vertex Fraction (JVF) [152] was used to discriminate between jets

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<sup>1</sup> Such stability criteria ensure that cross sections calculated at parton level are comparable to measurements of hadronic jets which necessarily include non-perturbative hadronisation effects.

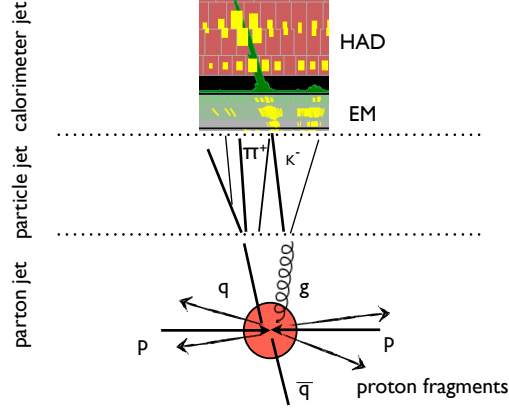


Figure 33: Schematic view of the production of jets from a hard scattering interaction and the possible definitions of different jet levels.

coming from the primary vertex of interest and jets coming from other vertices. The JVF of the  $i$ -th jet with respect to the  $j$ -th PV, is defined as:

$$\text{JVF}(i, \text{PV}_j) = \frac{\sum_k p_T^{\text{track}_k^i, \text{PV}_j}}{\sum_n \sum_l p_T^{\text{track}_l^i, \text{PV}_n}} \quad (71)$$

where  $k$  runs over all tracks coming from  $\text{PV}_j$  matched to the  $i$ -th jet,  $n$  runs over all PVs. Ideally, jets coming from pile-up interaction might have low value of JVF while jets originating from the chosen PV will have  $\text{JVF}=1$ .

In Run2, the increased pile-up conditions required a different approach. A new multivariate discriminant, the Jet Vertex Tagger (JVT) [153] was introduced. JVT technique uses a combination of track-based variables to calculate the likelihood that a jet originates from the hard-scatter process ( $\text{JVT} \sim 1$ ) more than from pile-up ( $\text{JVT} \sim 0$ ).

### Jet Energy Calibration

After the jet finding procedure, the jets are at the EM scale and need to be corrected to the hadronic scale (see Figure 33) by including the estimated hadron response obtained with MC simulation [154, 155].

Figure 34 shows an overview of ATLAS calibration scheme for EM-scale calorimeter jets used in the Run2. Each stage of the calibration corrects the full four-momentum, scaling the jet  $p_T$ , energy, and mass.

The first correction is applied to the jet direction to make the jet pointing back to the hard-scatter primary event vertex rather than to the nominal center of the ATLAS detector.

The pile-up correction of the jet response is applied to remove the excess energy resulting from the in-time and out-of-time pile-up. The correction is based on the “Jet-area method” [156], which is an area-based  $p_T$  density subtraction and a residual correction derived from the MC simulation. It makes use of the median  $p_T$  density  $\rho$  in the

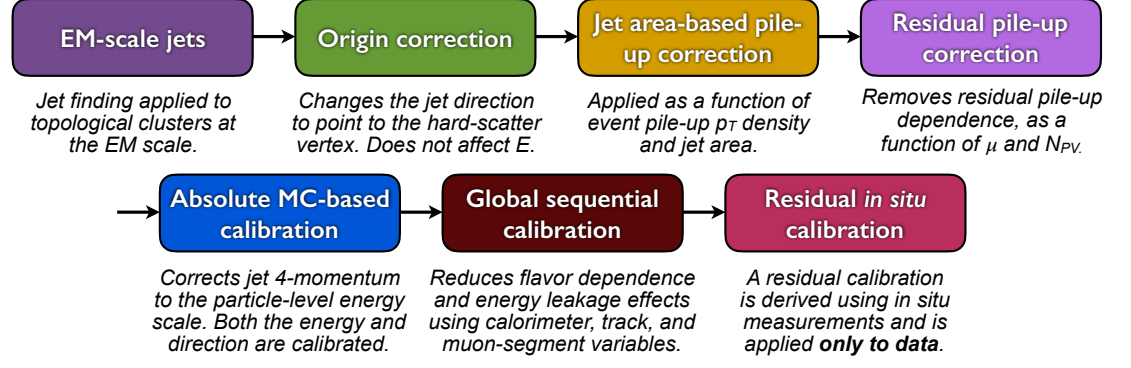


Figure 34: Calibration stages for EM-scale jets. Other than the origin correction, each stage of the calibration is applied to the four-momentum of the jet. Figure is taken from [155].

$\eta, \phi$  plane of the event, and the area of the jet in this plane  $A_{\text{jet}}$ . The quantity  $\rho \cdot A_{\text{jet}}$  gives an estimate of the pile-up contribution to the jet, which is subtracted from the jet four momentum. Since  $\rho$  is derived from the central, lower-occupancy regions of the calorimeter, a residual correction derived from the MC simulation is applied in order to fully describe the pile-up sensitivity in the forward calorimeter region or in the higher-occupancy core of high- $p_T$  jets. In the end, the pile-up corrected  $p_T$  of the jet is given by:

$$p_T^{\text{corr}} = p_T^{\text{reco}} - \rho \cdot A_{\text{jet}} - \alpha \times (N_{PV} - 1) - \beta \times \mu \quad (72)$$

where  $\alpha$  and  $\beta$  parameter are derived from the residual dependence in the nominal MC sample and  $\mu$  is the average number of interactions per bunch crossing and

The jet energy calibration (Jet Energy Scale) is a multiplication by the average jet energy response. The JES is derived by calculating the response function between the reconstructed jet energy and their particle-level constituents in MC simulated events. Jet energy needs also correction for pile-up effects and to make the jet point to the primary event vertex instead of the center of the ATLAS detector.

The average energy responses is derived as a function of  $\eta_{\text{det}}^2$  and jet- $p_T$ .

Further corrections are implemented to address the sensitivity of the calorimeter response and the jet reconstruction to fluctuations in the jet particle, which are due to different composition and distribution of energy within the jet. This is caused by difference in the initiating particles, most notably between quark- and gluon-initiated jets, where the first type tends to lead to harder jet  $p_T$  distribution while the second results in more particles of softer  $p_T$ . The resolution on the jet energy scale (JES) is then improved using a global sequential calibration calculating jet  $p_T$  response in MC simulation as a function of several observables, which is the same procedure as used in Run1 [157].

<sup>2</sup>  $\eta_{\text{det}}$  is the jet  $\eta$  pointing from the geometric center of the detector.

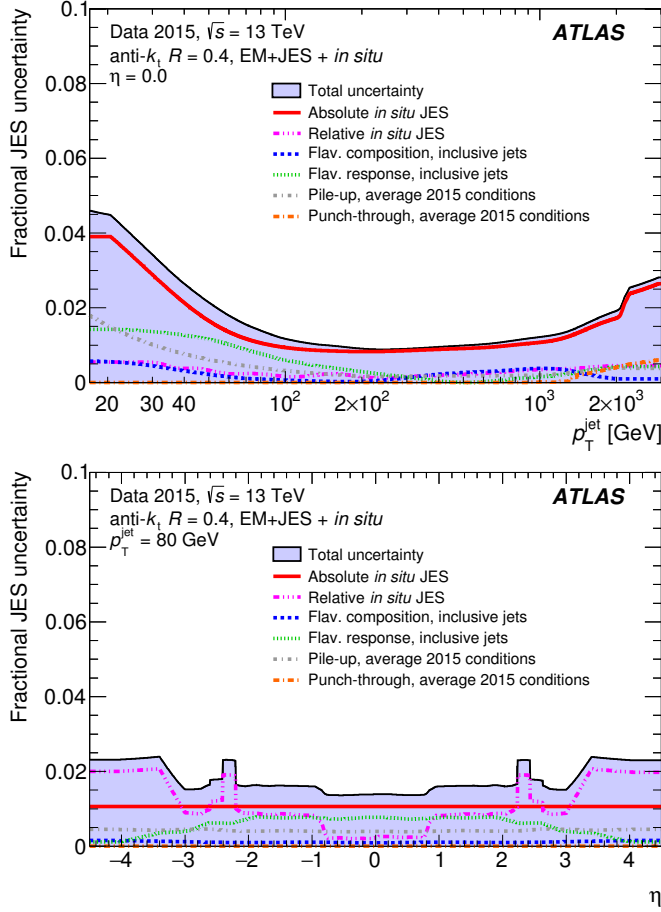


Figure 35: Combined uncertainty in jet energy scale systematic uncertainty of fully calibrated jets as a function of the jet  $p_T$  for central jets ( $|\eta| = 0$ ) and as function of  $\eta$  for jets with  $p_T = 80$  GeV. The contributions from each source of uncertainty is shown separately. Figure is from [155].

Finally, in situ techniques are used to measure the difference in jet response between data and MC simulation which may lead to miscalibration of jet energy, with residual corrections applied to jets in data only. It is derived exploiting the case of events where a balance in the transverse plane between jets and a well-calibrated object is present. The reference object is either a photon or a Z boson. The double-ratio:

$$f = \frac{p_{T,MC}^{\text{jet}}/p_{T,MC}^{\text{ref}}}{p_{T,data}^{\text{jet}}/p_{T,data}^{\text{ref}}} \quad (73)$$

is used to correct for differences between the energy scale of the jets reconstructed in data to those in simulation.

### 5.2.3 Jet Energy Scale and Resolution Uncertainties

For analyses dealing with jets the uncertainty on the Jet Energy Scale (JES) and resolution (JER) calibrations is an important systematic. Uncertainties on the JES and JER also have a direct impact on the determination of the missing transverse energy, which make their understanding and estimation crucial for the correct analysis of the collected data and simulation. The uncertainty of JES has several components, such as in situ calibration uncertainties, pile-up uncertainty, flavor composition and flavor response uncertainty.

These uncertainties for the central region are shown in Figure 35 together with the total JES uncertainty. The JES uncertainty is found to be around 4.5% at low  $p_T$  and decreasing to 1% in the jet  $p_T$  region of 100-1000 GeV.

The jet energy resolution is measured from calorimeter observables by exploiting the  $p_T$  balance in events containing high- $p_T$  jets with two in situ techniques already used in 2011 for collisions at 7 TeV: dijet balance and bisector method [158]. The impact on JER calculation due to the changes in the detector between Run1 and Run2 have been evaluated using MC simulations. Uncertainties on the jet resolution and also those related to the pile-up on the JES have been derived for the full  $\eta$  range of the detector.

## 5.3 JET RECLUSTERING ALGORITHM

The standard jet cone radius of the Anti- $k_t$  jet collection used by the ATLAS analyses is  $R = 0.4$ . Larger radius jets, e.g.  $R \geq 1.0$  are commonly used to fully capture the decay products of boosted heavy particles at the LHC. Grooming techniques are used to suppress soft components like UE and pile-up.

One possibility to access to such a larger radius jet is to fix the clustering radius and the grooming parameter to a larger value, provided that calibrations and uncertainties do not exist for a scan in jet radii and in grooming parameters but only for a small choice of values.

An alternative approach is the jet *reclustering* algorithm [159]: jet of small radius  $r$  built from topological clusters calibrated at the EM scale are taken as input to a further clustering algorithm of large- $R$  radius "reclustered" jets, with  $r \leq R$ . The fully calibrated input small jets can make the calibration of the re-clustered large radius jets automatic, while corrections and systematic uncertainties associated with the input jets are inherited as well for the large radius case. Furthermore, jet grooming can be added to the reclustering process in such a way that the grooming parameters can also be optimized offline.

The application of the reclustering algorithm in the ATLAS experiment [160] proceeds as it follows: calibrated jets with a radius parameter  $r = 0.4$  described above surviving the resolution of ambiguities are taken as input if they have  $p_T > 25$  GeV. This minimum  $p_T$  threshold acts as an effective grooming for the reclustering. As shown in Figure 36, there

are many more constituents far away from the jet axis (which have low  $p_T$ ) in the blue large radius jet than those within the re-clustered jet. This property also makes reclustered jets have a smaller area and thus be less pileup susceptible. A further grooming scheme called *re-clustered jet trimming* is subsequently applied to remove any small radius jet constituent  $j$  within a re-clustered large- $R$  jet  $J$  if  $p_T^j < f_{\text{cut}} \times p_T^J$ , where the parameter  $f_{\text{cut}}$  is set to be 0.05. It is remarkable that the  $f_{\text{cut}}$  is applied to already calibrated jets  $p_T$ , differently from the case for standard large radius jet trimming. The effect of the trimming procedure on the reclustered jets is shown in Figure 37. The pile-up corrections to the small radius jets propagate to the reclustered as the other corrections.

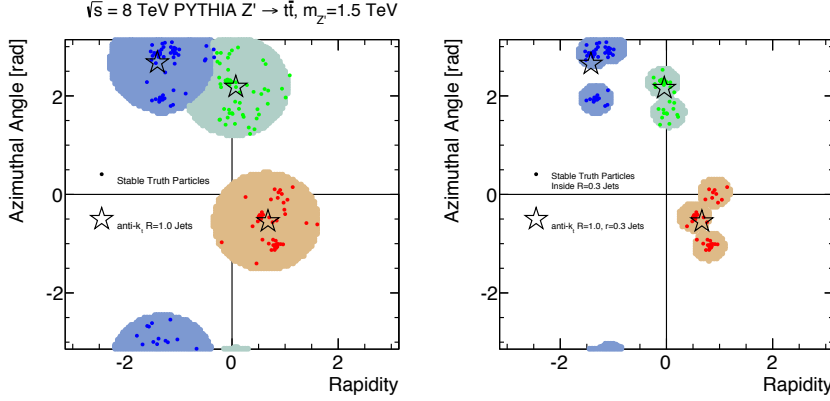


Figure 36: Comparison between events which have been clustered using the Anti- $k_t$  with  $R = 1.0$  (left) and with Anti- $k_t$   $r = 0.3$  reclustered to  $R = 1.0$  (right). The shaded regions show the jet area determined by clustering ghost particles. Figure is from [160].

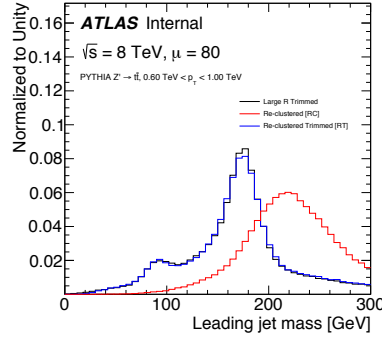


Figure 37: Leading jet mass comparison between reclustered jets (RC), reclustered trimmed jets (RT), standard large- $R$  trimmed jets for a benchmark sample of a  $Z \rightarrow t\bar{t}$  generated with  $\mu = 80$ . Figure is from [160].

#### 5.4 BOTTOM QUARK TAGGING

The identification of jets initiated by  $b$ -quarks ( $b$ -tagging) plays an important role in the analysis of physics data collected at hadron colliders, for their presence in many final states of physics processes of interest as well as for reducing background processes containing light-flavor jets.  $b$ -tagging is used in analyses measuring the properties of the top quark, searches for the Higgs boson decaying to a  $b$ -quark pair ( $H \rightarrow b\bar{b}$ ) and searches for new physics phenomena with decays to heavy flavour quarks.

The decay into  $b$ -quarks means the creation of  $B$ -hadrons.  $B$ -hadrons have a relatively long lifetime, of the order of 1.5 ps ( $c\tau \sim 450 \mu\text{m}$ ). A  $B$ -hadron with  $p_T = 50 \text{ GeV}$  will thus travel ca 3 mm in the transverse plane before decaying, leading to topologies with at least one vertex displaced from the interaction point. Jets originating from  $b$ -quarks ( $b$ -jets) can therefore be identified by reconstructing the displaced vertex and by studying the impact parameters of tracks: the jet can be therefore  $b$ -tagged. The tracker systems are designed to have a fine enough resolution to detect the  $B$ -hadron decay as a secondary vertex.

Various algorithms have been developed in ATLAS to identify  $b$ -jets [161]. The  $b$ -tagging algorithm considered in this analysis is called MV2c10 and is based on a multivariate discriminant obtained using Boosted Decision Trees (BDTs) [162, 163]. The inputs for the BDTs are the outputs of three separate  $b$ -tagging algorithms: the impact parameter based algorithm  $IP3D$ , the secondary vertex finder algorithm  $SV$ , and the decay chain multi-vertex algorithm  $JetFitter$ . All of them exploit the tracks associated with a jet to form continuous discriminating variables potentially useful for the secondary vertex identification.

##### *Impact Parameter Tagger $IP3D$*

The  $IP3D$  algorithm is based on the significance of the transverse and longitudinal impact parameters. The sign is assigned with respect to the direction of the jet under consideration. Secondary vertices behind the primary are normally due to background and are used to help to calibrate the light quark tag rate. Tracks associated with a  $b$ -jet are tend to have large impact parameters with respect to those originating from the primary vertex.  $IP3D$  uses a log-likelihood ratio (LLR) as discriminant. The LLR is calculated as  $\sum_{i=1}^N \log \frac{p_b}{p_u}$  where  $N$  is the number of tracks of a given jet and  $p_b$ ,  $p_u$  are the template probability density functions (PDF) for the  $b$ -jet and light-flavour jet hypotheses. An alternative algorithm that only uses the transverse impact parameter is called  $IP2D$ .

##### *Secondary Vertex Tagger $SV$*

The secondary vertex algorithm aims at explicitly reconstructing displaced, secondary vertices from tracks selected as not originating from decays of long-lived particles (as  $K_S$  or  $\Lambda$ ), photon conversion or hadronic



interaction with the matter of the detector. The removal is performed testing all track pairs within a jet for a two-track vertex hypothesis. The probability to reconstruct the secondary vertex of a b-jet depends on  $p_T$  and is between 70% to 80%.

#### *Decay Chain Reconstruction Tagger JetFitter*

*JetFitter* is a decay chain reconstruction algorithm which aims at reconstructing the full hadron decay chain (from  $b$ - and  $c$ -quarks) by studying the topological substructure of the jet. It uses a Kalman filter to define the trajectory that the three decay (primary, bottom and charm) vertices lie on. With this approach, the  $B$ - and  $C$ -hadron vertices, whenever resolution allows, can be resolved, even when only a single track is attached to any of them. The discrimination is obtained from a likelihood including track and vertex variables, as well as the flight length significances for each vertex [164].

#### 5.4.1 *Boosted Decision Tree Algorithm MV2*

The vertex-based algorithms performs much lower mistag rates than the *IP3D*, but their efficiency for actual  $b$ -jets is limited by the low secondary vertex finding efficiency. The results of such different approaches are therefore combined to define more versatile and powerful tagging algorithms. The final product, called the MV2 algorithm, uses a Boosted Decision Tree. The BDT is trained using a large simulated  $t\bar{t}$  sample, which naturally contain a high fraction of  $b$ -jets, with jets labelled as signal or background using truth-tagging, which looks for a  $b$ -hadron inside the jet cone. If no  $b$ -hadrons are found, then the procedure is repeated with  $c$ -hadrons. Jets not truth-tagged fall into the light-jet category. The BDT can be trained with varying proportions of charm jets. The default training used by ATLAS in Run2 is called MV2c10, where the background is composed of 20%  $c$ -jets. At an operating point corresponding to 77%  $b$ -jet acceptance, it rejects a 40% more light-jets and 4 times more  $c$ -jets than its Run1 predecessor MV1c[163]. Different operating points are supported by the ATLAS software. They are calibrated to account for any differences between simulation and data. Figure 38 shows MV2c10 BDT output for the signal and background components. Figure 39 shows latest  $b$ -tag efficiency results.

## 5.5 ELECTRONS AND PHOTONS

Both electrons ( $e$ ) and photons ( $\gamma$ ) create showers contained only in the electromagnetic calorimeter. They may result in similar detector responses in the EM calorimeter, albeit electrons are expected to have one track matched with an energy deposit in the calorimeter while photons can either go under electron pair conversion through the interaction with the detector material ( $\gamma \rightarrow e^+e^-$ ), resulting in no associated tracks, or be unconverted with no tracks associated to an energy deposit.

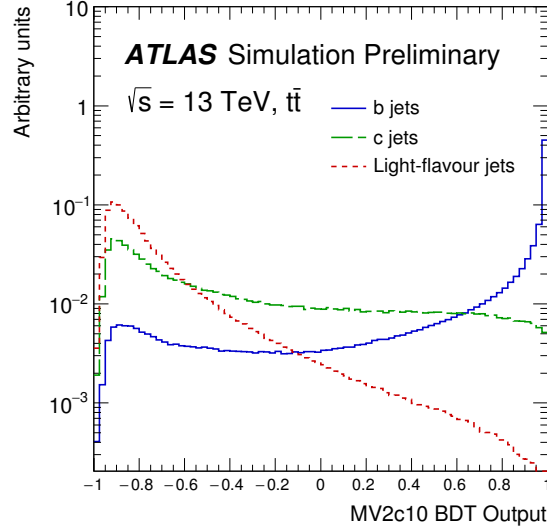


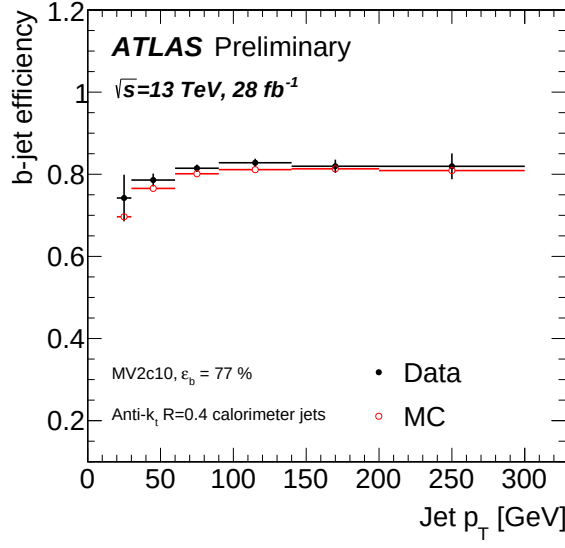
Figure 38: MV2c10 BDT output for  $b$ - (solid blue),  $c$ - (dashed green) and light-flavour (dotted red) jets evaluated with  $t\bar{t}$  events. Figure is from [163].

#### 5.5.1 Electrons

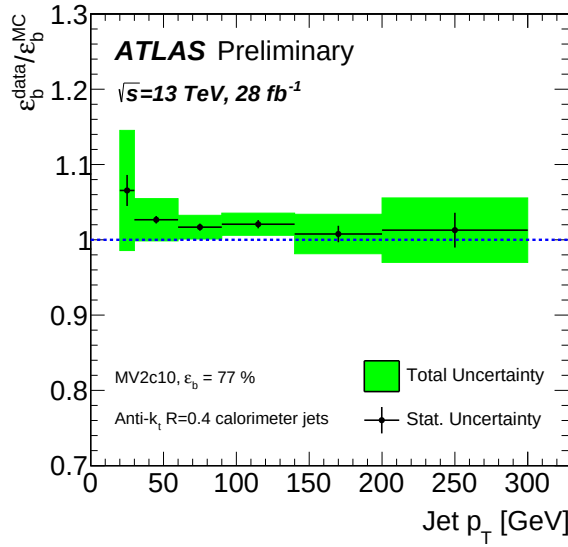
The electron reconstruction [166] in the central region of the ATLAS detector ( $|\eta| < 2.47$ ) starts from cluster seeds in the EM calorimeter which are then associated to reconstructed tracks of charged particles in the ID.

The EM calorimeter is segmented into towers of size  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ . The energy deposit of all cells within a tower is summed and form the basis for identifying cluster seeds. These clusters are seeded by towers with total transverse energy above a threshold of  $E_T > 2.5$  GeV and searched for by a sliding-window algorithm [149], with a window size of  $3 \times 5$  towers. If there are neighbouring clusters, the duplicated clusters are removed. A further cleaning is performed in order to isolate the seed clusters. A region of interest with a size of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  around the cluster is defined and tracks with  $p_T > 1$  GeV found within the region of interest are matched to the cluster. An electron candidate must have at least one track associated to the energy deposit in the cluster. If more than one track is matched with the cluster, tracks with hits in the silicon detectors have higher priority. The track with the smallest distance  $\Delta R$  to the centre of the cluster is chosen. Electron candidates without any associated precision hit tracks are removed and considered to be photons. Energy losses in the ID due to bremsstrahlung are included by refitting the matched tracks with a Gaussian Sum Filter (GSF) algorithm [167], which takes in account the non-linear bremsstrahlung effects and yields a better estimate of the track parameters.

The energy of the electron cluster is finally collected using  $3 \times 7$  towers of cells in the EM barrel region and  $5 \times 5$  towers of cells in



(a)



(b)

Figure 39: [Top] b-tagging efficiency for the MV2c10 b-tagging algorithm at the 77% working point as a function of jet  $p_T$ , extracted from data using  $e\mu + 2$  jets events and a tag-and-probe method (black, solid circles), and in a  $t\bar{t}$  Monte Carlo simulation (red, open circles). [Bottom] Ratio of b-tagging efficiency in data and simulation for the MV2c10 b-tagging algorithm at the 77% working point as a function of jet  $p_T$ , extracted using the same samples as top plot. Figures from [165].

the EM end-caps. The calibration is performed on the energy deposit in each of the calorimeter layers. MC-based response for calibration of the clusters, corrections due to variations in special detector regions not included in the simulation are also included in the calibration [168]. The overall electron response in data is calibrated so that it agrees with the expectation from simulation, using a large sample of  $Z \rightarrow e^+e^-$  events. The energy calibration is then validated with other processes.

Not all reconstructed electrons are prompt true electrons but they suffer large backgrounds from different sources such as mis-identified hadrons arising as jets passing the electron reconstruction, photon conversions, and semi-leptonic heavy-flavor decays. Additional dedicated likelihood electron identification (ID) criteria are applied to increase the purity of reconstructed objects. The identification is based on variables sensitive to several properties: the longitudinal and transverse shape of the shower is required to be consistent to those expected from electrons in the EM calorimeter; a selection is put on the properties of the tracks, such as the number of hits in the TRT associated with the track, and a measured hit in the innermost layer of the pixel detector has to be present to discriminate against photon conversions (if the transversed module is active); the matching of the tracks to the cluster is subject to a veto on reconstructed photon conversion vertices associated with the cluster [166].

While in Run1 both a sequential cut-based and multivariate likelihood-based (LH) electron identification procedures were developed [169], for Run2 only the LH identification has been re-optimised [170]. It is a multivariate analysis (MVA) technique that simultaneously evaluates several properties of the electron candidates when making a selection decision. The LH method uses the signal and background probability density functions (PDFs) of the discriminating variables. This allows for better background rejection for a given signal efficiency than a cut-based algorithm that would use selection criteria sequentially on each variable. Three LH selections are defined: *Loose*, *Medium*, and *Tight*. As the tightness increases, background-rejection is improved while the electron identification efficiency is lower. The *Loose* selection is specialised in rejecting light-flavoured jets, while in the *Medium* and *Tight* selections additional variables are included in order to reject electrons from converted photons or heavy flavour hadronic decays.

The identification efficiencies are measured in  $Z \rightarrow ee$  and  $J/\Psi \rightarrow ee$  events, using a *tag-and-probe* technique [166, 170], where one electron is "tagged" using strict cuts and the efficiency is measured on the other, "probed" electron. This method delivers sufficient data events to cover a range in  $E_T$  from 7 to 200 GeV and  $|\eta| < 2.47$ , with a good granularity. The low  $E_T$  range (typically from 7 to 20 GeV) is covered by the  $J/\psi \rightarrow ee$  decays, while  $Z \rightarrow ee$  events are used for measurements above 15 GeV. The efficiency to find and select an electron in the AT-

LAS detector is measured as a product of different components, namely reconstruction, identification, isolation, and trigger efficiencies:

$$\epsilon_{\text{tot}} = \epsilon_{\text{reco}} \times \epsilon_{\text{ID}} \times \epsilon_{\text{isol}} \times \epsilon_{\text{trigger}} \quad (74)$$

The  $ee$  line-shape for the calibrated data compared with the corrected simulation, and the identification efficiencies for various selection criteria measured in  $Z \rightarrow ee$  decays are shown in Figure 40.

### 5.5.2 Photons

Photon reconstruction [172, 173] proceeds likewise the electron reconstruction, as the photons interact electromagnetically and produce showers in the EM calorimeter (ECAL). The energy deposits in clusters of cells in the EM calorimeter form the seeds for the photon reconstruction, requiring little or no energy deposit in the hadronic calorimeter (HCAL). Once the clusters are found, tracks from the inner detector are matched to the cluster. Photons are electrically neutral, so they do not leave a track in the inner detector. Nonetheless, they can convert to an electron-positron pair in the presence of detector material. If a cluster in the ECAL has no associated tracks, cluster is reconstructed as *unconverted photon* [173].

*Converted photons* require a cluster with at least one matched track associated to a conversion vertex, which are vertices in the ID typically with two oppositely charged tracks emerging in parallel from the vertex or with a single track where energy deposited in the calorimeter is much larger than the momentum of the track. If the matched track is consistent with originating from a photon conversion into an electron-positron pair, and if in addition a conversion vertex is reconstructed, the corresponding candidates are considered as converted photons. They are classified as *single-track* or *double-track* conversions depending on the number of assigned electron-tracks. To discriminate from electrons produced at interaction point, the track must have no hits in the innermost layer of the pixel detector. The photon reconstruction efficiency, measured in MC simulations [174], is of 96% of prompt photons with  $E_T > 25$  GeV reconstructed as photon candidates, while the remaining 4% are incorrectly reconstructed as electrons but not as photons.

The energy of the photons are measured in clusters with a size depending on whether the photon is converted or not. The energy of the photon is calibrated using the same procedure used in the electron energy calibration.

The reconstructed photon sample contains prompt photon of interest and background photons originating from misidentified jets with a substantial portion of energy in the HCAL and a broader transverse energy deposit in the ECAL. Those hadronic background photons come mostly from the decay of neutral particles ( $\pi^0$ ,  $\eta$ ). As the shower of real prompt photons is typically narrow and contained in the ECAL with limited leakage into the HCAL, those properties, both in its second sampling layer and in the strips, are used for prompt photon ID. Two sets of

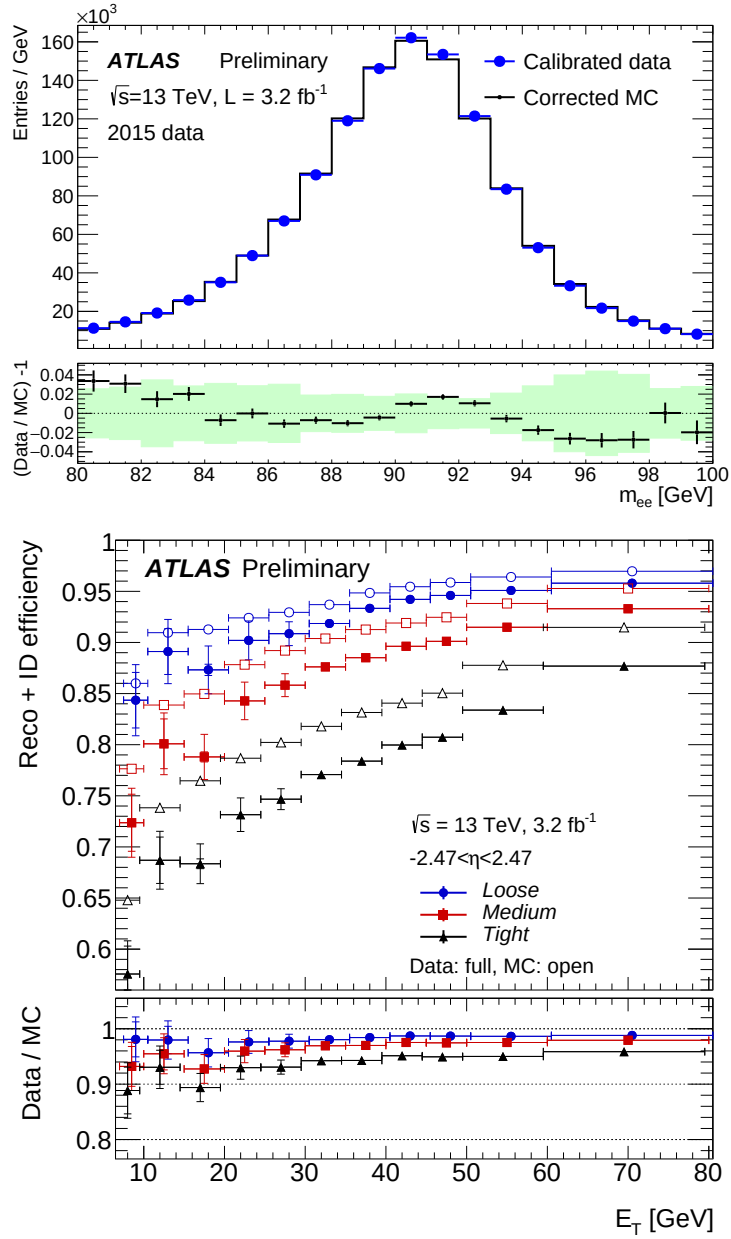


Figure 40: [Top:] Electron pair invariant mass distribution for  $Z \rightarrow ee$  decays in data and improved simulation. Energy scale corrections are applied to the data. The improved simulation is shown before and after energy resolution corrections, and is normalised to the number of events in data [171]. [Bottom:] Combined electron reconstruction and identification efficiencies as a function of  $E_T$  for the LH loose, medium and tight selections, compared to MC expectation for electrons from  $Z \rightarrow ee$  decay. The uncertainties are statistical (inner error bars) and combined statistical+systematic (outer error bars) [166].

photon ID selection are used [172]: a *Loose* selection based solely on shower shape and energy deposit in the HCAL, typically used for the trigger and for background studies; a *Tight* selection exploiting the full granularity of the ECAL, which provides good rejection of hadronic jets where a neutral meson carries most of the jet energy ( $\pi^0 \rightarrow \gamma\gamma$ ).

Background photons have usually a sizable surrounding hadronic activity, with a poor isolation. Therefore, identified prompt photons must pass an isolation criterion to further resolve ambiguities with candidate jets: the transverse energy in a cone of size  $\Delta R = 0.4$  around the identified photon  $E_T$  must not exceed 4 GeV.

Since there is no single physics process that is able to produce a very clean sample of prompt photons spanning over a large  $E_T^\gamma$  range, the photon identification efficiency is measured with three different data-driven methods, each optimised for a window of photon energy [172]:

- selecting photons from radiative decays of the  $Z$  boson allows a precise measurement in the low  $E_T$  region;
- extrapolating photon properties from  $Z \rightarrow ee$  decays covers an intermediate  $E_T$  range;
- estimating and subtracting from a control sample enriched with background photons the fraction of isolated photon candidates, for the very large  $E_T$  range.

The  $m_{ll\gamma}$  distribution measured in the first technique with a sample of  $Z \rightarrow ll\gamma$ , compared to the corrected simulation, and the different contributions to the total photon energy resolution uncertainty measured in the same sample are shown in Figure 41. The identification procedures provide an ID efficiency of 53-64% and 47-61% for, respectively, unconverted and converted photons at  $E_T \sim 10$  GeV, increasing to 88-92% and 96-98% for  $E_T > 100$  GeV.

## 5.6 MUONS

Muon travel through the calorimeters and eventually reach the muon spectrometer (MS), so that they can be fully reconstructed by performing a combination of the track left in the inner detectors and those in the MS. During the 2013-2014 shutdown, the muon reconstruction software was updated leading to an increase from 2 to 4 types of reconstructions defined for muons traversing the ATLAS detector [175]:

- *Combined* (CB) muons consists of tracks which have been independently reconstructed in the MS and ID and then combined using a global fit. Most muons are reconstructed following an outside-in pattern recognition (first reconstruction in MS, then matching to an ID track), while inside-out combined reconstruction is used as complementary.
- *Segment-tagged* (ST) muons are reconstructed from an ID track if, once extrapolated to the MS, the track is associated with at

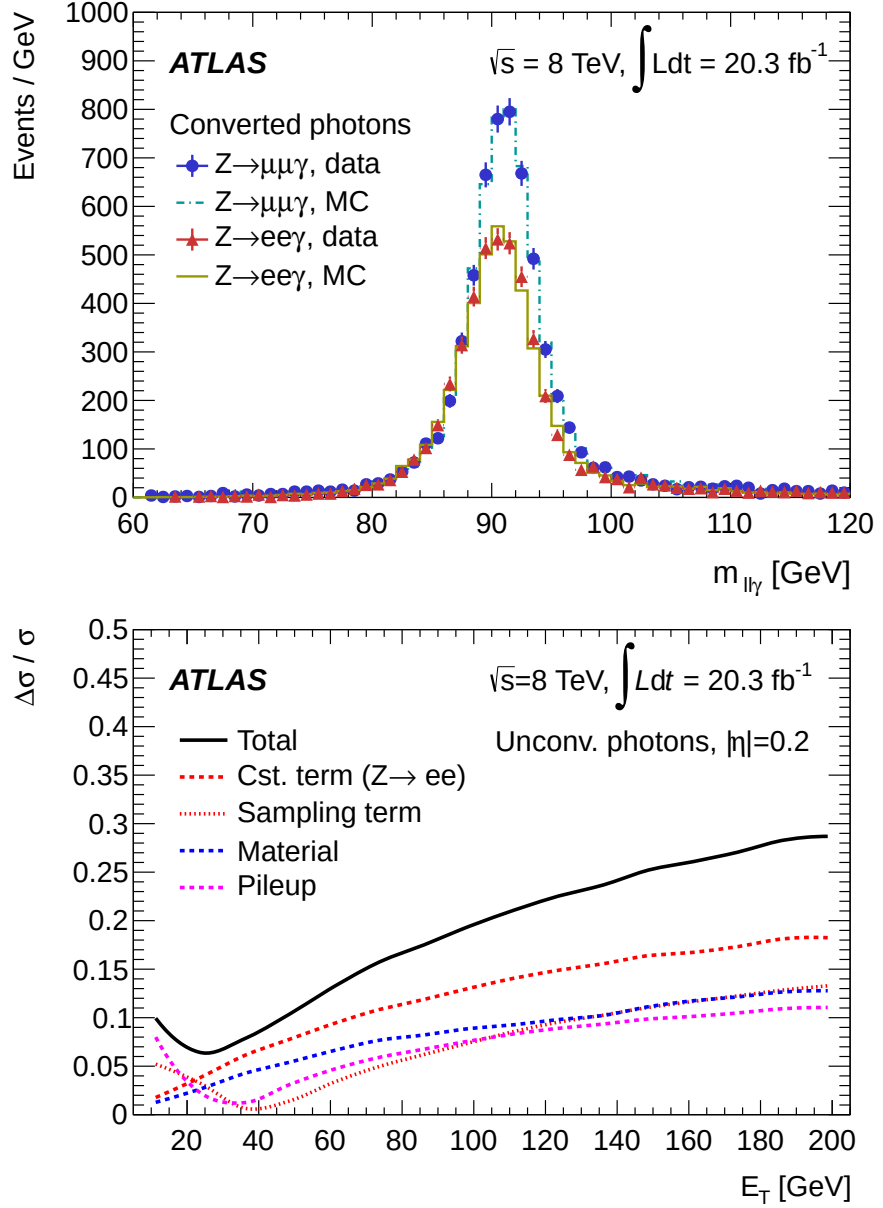


Figure 41: [Top:] Invariant mass distributions in data and simulation, for large-angle  $Z \rightarrow l l \gamma$  events with converted photons in the electron and muon channels, for  $\Delta R(l, \gamma) > 0.4$  and  $E_T^\gamma > 15$  GeV. Energy corrections are applied. The MC simulation is normalised to the number of events in data. [Bottom:] Contributions of the different uncertainties to the relative resolution uncertainty as a function of  $E_T$  for unconverted photons with  $|\eta| = 0.2$  [168].



least one local track segment in the MDT or CSC chambers. ST muons have either a low- $p_T$  or fall in regions with reduced MS acceptance ( $|\eta| \sim 0$  and  $|\eta| \sim 1.2$ ).

- *Calorimeter-tagged* (CT) muons are reconstructed by matching a track in the ID to deposits in the calorimeter compatible with a minimum-ionizing particle. The CT type has the lowest purity but they help in increasing acceptance in the region where the MS is only partially instrumented, i.e. around  $\eta = 0$ .
- *Extrapolated* (ME) muons whose trajectory is reconstructed from only a MS track extrapolated to the interaction point. ME muons are mainly used for muon reconstruction into the region  $2.5 < |\eta| < 2.7$ , which is not covered by the ID.

The muon reconstruction used in Run2 is defined as *Chain 3* [176], an improvement of those used in Run1. For Run-2, a dedicated prompt muon identification algorithm was optimised to select muons produced in the hard scattering and suppress background muons formed inside hadronic jets, mainly from  $\pi$  and K decays. Variables for background discrimination have been studied in simulated  $t\bar{t}$  events, where muons from W decays are defined as *high-purity* muons. The identification is based on the variables  $q/p$  significance<sup>3</sup>,  $\rho'^4$ , and the normalised  $\chi^2$  of the combined track fit.

Specific requirements on the ID tracks used for muon reconstruction are required: at least one Pixel hit and 5 SCT hits, and fewer than three Pixel or SCT holes, and that at least 10% of the TRT hits originally assigned to the track are included in the final fit, where the last requirement is only employed for  $|\eta|$  between 0.1 and 1.9, in the region of full TRT acceptance.

Four identification selections are defined: Medium, Loose, Tight, and High- $p_T$  [175]. The Medium selection is the default for baseline muons in Run2. The baseline selection requires the muons to pass the acceptance cuts  $p_T > 7$  GeV and  $|\eta| < 2.7$ .

Further requirements are applied to select high-purity muons. The transverse impact parameter significance of the track  $d_0/\sigma(d_0)$  has to be less than 3, the longitudinal impact parameter  $z_0 \sin \theta$  has to be less than 0.4 mm, and to satisfy *GradientLoose* isolation requirements [175] which rely on tracking-based and calorimeter-based variables. Finally, the leading, high-purity muon, is also required to have  $p_T > 27$  GeV.

The reconstruction efficiency is measured in  $Z \rightarrow \mu\mu$  events of low- $p_T$  muons using a sample of  $J/\psi \rightarrow \mu\mu$  events with a tag-and-probe method in both data and simulations. The resulting efficiencies as function of muon- $\eta$  and  $p_T$  are shown in Figure 42: the measured reconstruction efficiencies for selected muons is above 98% throughout the entire range

<sup>3</sup> Defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties

<sup>4</sup> Defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the  $p_T$  of the combined track [175].

with the exception of the central region of  $|\eta| < 0.1$ , where due to lacking instrumentation of the MS a drop to 65% is observed. The efficiencies are found to be stable as a function of the transverse momentum.

As the efficiency in data and simulated samples differ significantly, scale factors defined in  $\eta$  and  $p_T$ -bins are used to correct the simulation samples to the efficiencies measured in data.

### 5.7 MISSING TRANSVERSE MOMENTUM

In collider experiment the momentum in the plane transverse to the beam axis is conserved, implying that the sum of the transverse momenta of the collision products must remain zero as prior to the collision. If resulting particles escape ATLAS undetected, as for the case of neutrinos and other neutral weakly-interacting particles predicted in BSM scenarios, they will cause an imbalance in the transverse momentum of identified particles that can be used for their detection. The *missing momentum*  $\vec{p}_T^{\text{miss}} = \sum_i \vec{p}_T^i$ , where  $i$  runs on all *invisible* particles, can be also expressed as  $\vec{p}_T^{\text{miss}} = -\sum_j \vec{p}_T^j$ , where  $j$  runs now on all *visible* particles, by using the momentum imbalance in an event. The magnitude of this vector, assuming all invisible particles are massless is the *missing transverse momentum*:

$$p_T^{\text{miss}} = E_T^{\text{miss}} = |\vec{E}_T^{\text{miss}}| \quad (75)$$

Apart from invisible particles, other effects can contribute to the momentum imbalance, such as misreconstructed objects, imperfect resolutions, detector inefficiencies, cosmic-ray particles, and beam-halo particles, which may result in fake  $E_T^{\text{miss}}$ . A good measurement of the  $E_T^{\text{miss}}$  can thus also serve as an important measure of the overall event reconstruction performance.

The ATLAS  $E_T^{\text{miss}}$  reconstruction [177, 178], includes contributions from reconstructed and calibrated physics objects as electrons, photons, hadronically decaying tau-leptons, jets and finally muons, as well from soft-term contribution from detector signal objects not associated with any object. The x- and y-components of  $E_T^{\text{miss}}$  is then calculated as in Equation 76:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,e}} + E_{x(y)}^{\text{miss,\gamma}} + E_{x(y)}^{\text{miss,\mu}} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} \quad (76)$$

Differently from Run1, where the soft-term was reconstructed only based on topoclusters in the calorimeters not associated to any reconstructed particles [178], in Run2 the soft-term is estimated from tracks combined with information about hard objects in the calorimeter [177], an approach defined TST (track-based soft term).

From the  $x(y)$  components, the magnitude  $E_T^{\text{miss}}$  and the azimuthal angle  $\phi^{\text{miss}}$  can be calculated as:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (77)$$

$$\phi^{\text{miss}} = \arctan\left(\frac{E_x^{\text{miss}}}{E_y^{\text{miss}}}\right) \quad (78)$$

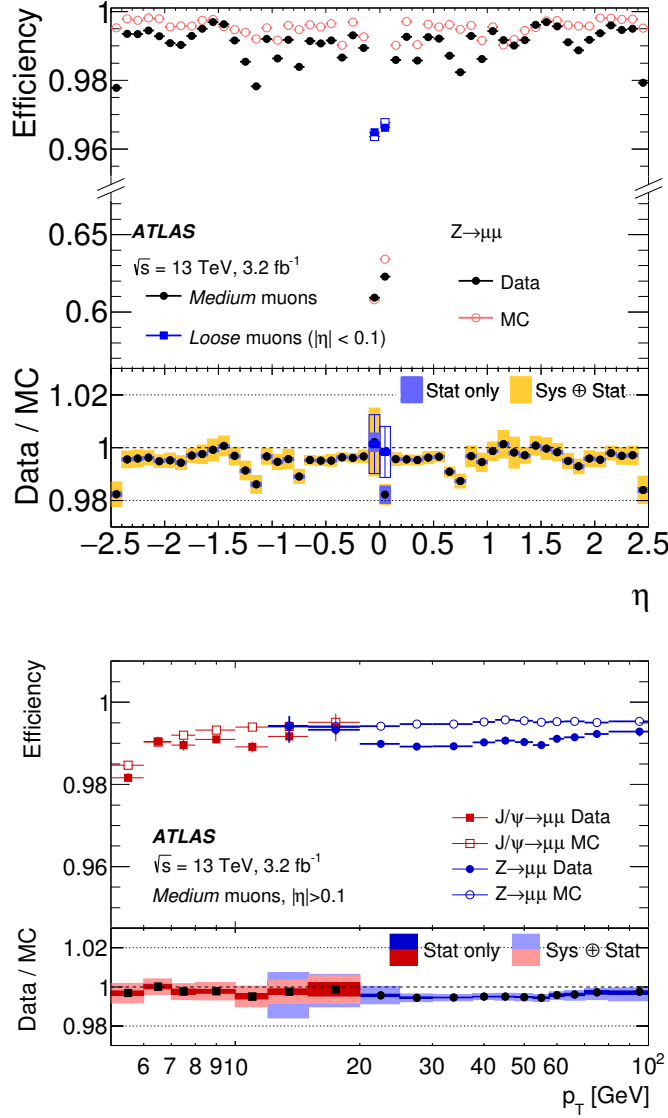


Figure 42: Measured reconstruction efficiency for the Medium muon selection as a function of the muon  $\eta$  (top) and efficiency of the Loose selection (squares) in the region  $|\eta| < 0.1$  where the Loose and Medium selections differ significantly. Signal muon sample is obtained from  $Z \rightarrow \mu\mu$  events. Reconstruction efficiency for the Medium selection as a function of the  $p_T$  of the muon (bottom), in the region  $0.1 < |\eta| < 2.5$  as obtained from  $Z \rightarrow \mu\mu$  and  $J/\psi \rightarrow \mu\mu$  events. Figures are from [175].

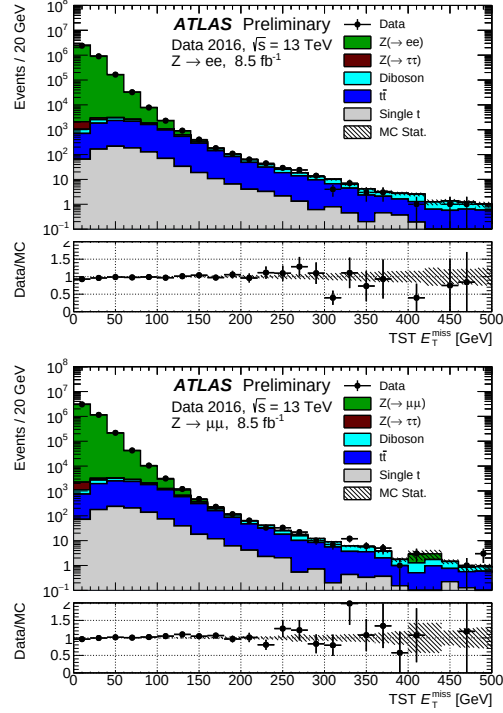


Figure 43: Distribution of  $\text{TST } E_T^{\text{miss}}$  in  $Z \rightarrow ee$  (top) and  $Z \rightarrow \mu\mu$  (bottom) events in the ATLAS 2016 dataset. The shaded band represents MC statistical uncertainty only. The  $\text{TST } E_T^{\text{miss}}$  reconstruction process uses reconstructed, calibrated objects to estimate the transverse momentum imbalance in the event. The Figure is taken from [179].

The  $E_T^{\text{miss}}$  reconstruction, both in the hard- and soft-term, is sensitive to the pile-up effect (Section 3.1.3), as tracks or objects might not be associated to the right vertex in case of multiple  $pp$  interactions. This may lead to mis-measurement of the  $E_T^{\text{miss}}$ . While the objects contributing to the hard term are fully calibrated and corrected for pile-up, the soft-term needs corrections in order to take in account this effect. The  $\text{TST } E_T^{\text{miss}}$  is in general more robust against pile-up as only hard scatter vertex is used. The agreement of the  $E_T^{\text{miss}}$  reconstruction between Run2 data and simulation after pile-up suppression is studied using  $Z \rightarrow ee/\mu\mu$  events and shown in Figure 43. The simulation results are in good agreement with data.

The  $E_T^{\text{miss}}$  resolution is investigated in  $Z \rightarrow ee$  events, in which no genuine  $E_T^{\text{miss}}$  is expected and studied as function of  $\sum E_T$  of the various processes and as a function of the number of primary vertices. As shown in Figure 44, reasonable agreement is found between data and MC simulation,

Systematic uncertainties on the calibrated physics objects are evaluated independently and propagated to the  $E_T^{\text{miss}}$  according to the Equation 76. The uncertainties caused by the soft-term account for a  $\approx 5\%$  uncertainty on both the scale and resolution of the missing transverse momentum [177].

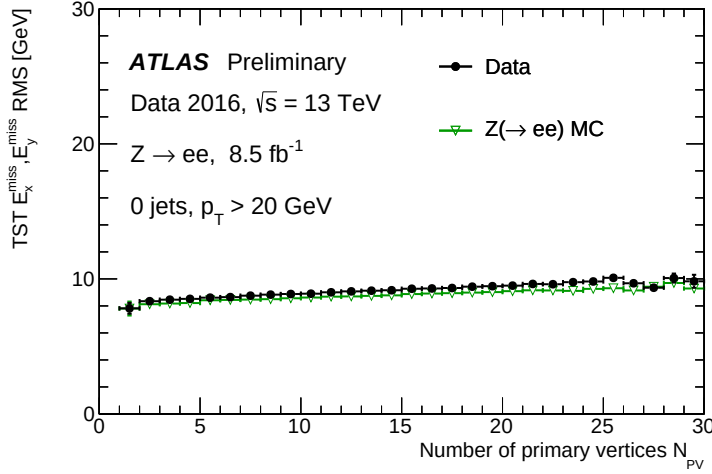


Figure 44: Distribution of  $\text{TST } E_T^{\text{miss}}$  resolution as a function of the number of primary vertices for a selection of Z boson decays to a pair of electrons. The Figure is taken from [179].

## 5.8 OVERLAP REMOVAL

After the objects reconstruction as described in the previous sections, remaining ambiguities between different objects may occur when candidates overlap with one another. Overlap removal procedure is performed in order to solve conflicts of overlapping candidates and classify them as single objects. The overlap criteria are based on the single distance given by  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ . The overlap removal is performed between jets with  $|\eta| < 2.8$ , leptons and photons by applying criteria in following order:

1. a jet found within  $\Delta R < 0.2$  of a baseline electron, not being a b-jet, is discarded. If it is identified as a b-jet, the electron is discarded;
2. an electron/muon and a jet passing the JVT selection are found  $0.2 < \Delta R < 0.4$ , the object is interpreted as a jet;
3. a muon and a jet are found in  $\Delta R < 0.2$  the object is interpreted as a muon, unless the jet satisfies  $N_{\text{trk}} < 3^5$ .

Additional overlap removal criteria resolving overlaps containing photons are used in regions where photons are selected and described later in Section 7.5.

<sup>5</sup>  $N_{\text{trk}}$  is the number of tracks with  $p_T^{\text{track}} > 0.5$  GeV associated with the jet



Part III

ANALYSIS





This thesis focuses on the search for new particles predicted by SUSY theory. Sparticles can decay in many various ways depending on the mass spectrum and mixing angle matrices. Many searches for SUSY with the ATLAS detector follow a similar pattern, targeting the selection of events with topologies comparable to those predicted coming from production and decay of SUSY particles. The expected signal yield is enhanced by such a selection relatively to the SM backgrounds.

This chapter contains an introduction to the strategy pursued and the methods employed by the inclusive search of strongly produced SUSY particles decaying in final states with jets and missing transverse momentum, carried out within the ATLAS collaboration at a collision energy  $\sqrt{s} = 13$  TeV, included in this thesis and described in details in Chapter 7.

### 6.1 ANALYSIS STRATEGY

The analysis here described is performed in *signal regions* (SRs), kinematic regions in phase space designed to include events in which SUSY particles are produced and where the background processes are suppressed. The SRs are optimised with procedures relying on the concept to find traits of the signal kinematic that are not present in the SM background behaviour, typically from the shape of the event distributions in some distinctive variables. The background processes can be *reducible*, i.e. processes whose final state is different from the one of interest but effectively mimicing it due to mismeasurements or object misidentifications, as happens with the multijet background; or the background can be *irreducible*, as the one coming from  $Z(\rightarrow \nu\nu)+\text{jets}$ , where the  $E_T^{\text{miss}}$  is real and the final state has the same topology as the process of interest. However, the rejection of the entire background is usually not reachable and there will still be events from background processes in the final selected dataset. This procedure takes the name of *cut-and-count* analysis, where the total amount of events  $N$  passing the selection cuts is counted and compared to the expected number of background events  $N_{\text{exp}} \pm \sigma_{\text{exp}}$  in the SRs.

The method to estimate the contribution from the major background processes relies on *control regions* (CRs), regions in phase space enriched in a particular background and orthogonal to the SRs. The method has been developed in order to overcome the infeasibility of taking the SM processes prediction directly in the SRs. As we access phase space of very high  $p_T$  and  $E_T^{\text{miss}}$ , which have not been well measured before, the SM prediction from simulated events is not completely reliable. It often happens that simulations can effectively describe the shape of distributions whilst having the normalization off.

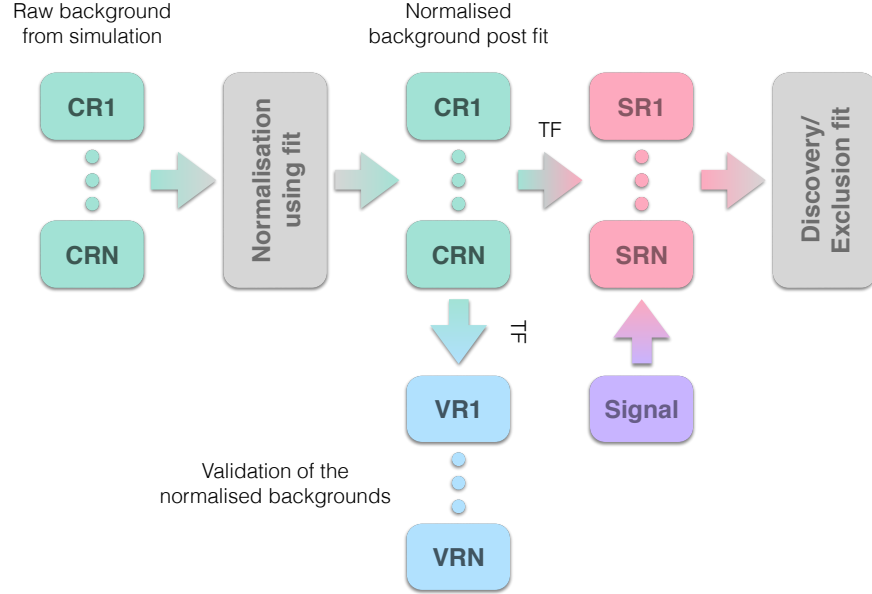


Figure 45: A schematic overview of a SUSY analysis from the background estimation to the result interpretation.

In order to constrain the normalisation of the background processes in the corresponding CRs, a simultaneous likelihood fit is performed. The number of background events in the signal regions is estimated using *transfer factors* (TF), that transfer the background estimate from CRs to SRs via formulas as Eq. (79):

$$N_{\text{SR}}^{\text{SM}} = N_{\text{CR}}^{\text{SM}} \times \text{TF}_{\text{CR} \rightarrow \text{SR}} \quad (79)$$

The likelihood fit allows to correctly account for the uncertainty on background estimates. The robustness of the background estimation is then tested in *validation regions* (VRs), regions with a selection closer to the one applied in the SRs but still having a low expected signal contamination.

After the background estimation, the number of observed events in the SRs are compared to the number of expected events from the background processes to test the validity of the Standard Model hypothesis as well as the hypothesis coming from the model of interest. In case an excess of observed event is reported, a discovery fit is performed to find the significance of the excess. Otherwise, an exclusion fit is performed setting both model-independent limits on visible cross section and model-dependent limits in the SUSY parameter-space.

A schematic overview of the entire analysis procedure is shown in Figure 45.

## 6.2 SIGNAL REGIONS

The SRs are defined as a set of selection cuts optimised in order to enhance the contribution of the SUSY signal and reduce the contribu-

tion from the background. The optimisation is performed by using the Monte Carlo simulation of SUSY signals and the SM background processes. Depending on the event topology investigated, i.e. on the mass spectrum of the sparticles considered in the SUSY model and how they decay, several cuts are set on distinctive variables. For example, the number of jets in the final state can vary depending on the sparticle considered (squarks or gluinos, for a strong production SUSY search), on the decay chain (direct or N-step decay) or on the lifetime. Besides, the missing transverse momentum can vary depending on the mass splitting between the primary produced sparticle and the LSP. Therefore, in an inclusive analysis where several models can be investigated in the same final state, multiples SRs are defined in order to fully cover the mass parameter space of the models of interest.

The SRs can either be orthogonal or inclusive, depending on the selection cuts chosen. Orthogonal signal regions are mutually exclusive and they can all be combined into one for every point of the signal grid. Inclusive signal regions can have overlaps resulting in the same event entering different regions and one signal region is fitted at a single time. Generally, orthogonal SRs require a larger data-sample as each signal region must be populated to ensure the stability of the fit. For this reason, the analysis presented here utilizes inclusive SRs.

### 6.3 DISCRIMINATING VARIABLES

The following variables are used to discriminate between the signal and the background in the definition of the signal regions.

$E_T^{\text{miss}}$  Missing transverse momentum, as described in Section 5.7. In a SUSY model, the LSP interacts weakly similarly to the neutrinos and will leave the detector untraced. This results in a momentum imbalance in the transverse plan.

$N_{\text{Jets}}$  Number of jets with  $p_T(\text{jet}) > 50$  GeV present in the event depending on the final state and on the event topology.

$\Delta\phi_{\text{min}}(\text{jet}, E_T^{\text{miss}})$  The minimal azimuthal angle between jet directions and  $\vec{E}_T^{\text{miss}}$  (often indicated as simply  $\Delta\phi$ ) is a powerful variable to reject multijet events with fake- $E_T^{\text{miss}}$  due to jet mismeasurement or due to neutrinos in jet coming from semi-leptonic decays of heavy flavour hadrons.

$m_{\text{eff}}$  The effective mass [180] is a measure of the energy-related activity in an event. It is defined as the scalar sum of the  $E_T^{\text{miss}}$  and the transverse momentum of the jets:

$$m_{\text{eff}} \equiv \sum_{i=1}^n |\mathbf{p}_T^{(i)}| + E_T^{\text{miss}} \quad (80)$$

where  $|\mathbf{p}_T^{(i)}|$  is the size of the transverse momentum vector of the  $i$ -th jet. The  $m_{\text{eff}}(\text{incl.})$  accounts for all the jets with  $p_T > 50$  GeV, while  $m_{\text{eff}}(N_J)$  only for a specific jet multiplicity.

$H_T$  is the jet-activity in the event, defined as  $H_T \equiv m_{\text{eff}}(\text{incl.}) - E_T^{\text{miss}}$ .

$E_T^{\text{miss}}/H_T$  The missing transverse momentum *significance* measures the size of the  $E_T^{\text{miss}}$  compared to the resolution of the hadronic energy in the event. An high-value of  $E_T^{\text{miss}}$ -significance is typical for events with real  $E_T^{\text{miss}}$ , discriminating from events with fake  $E_T^{\text{miss}}$ . Additionally, a lower cut on this variable has been found to lead to enhanced sensitivity to models characterised by  $q\bar{q}$  production.

$E_T^{\text{miss}}/m_{\text{eff}}(N_J)$  has an additional reduction power in events with higher jet multiplicity, as in case of pair-production of high-mass gluinos.

**Aplanarity** is an event-shape variable defined as:

$$A = \frac{3}{2}\lambda_3 \quad (81)$$

where  $\lambda_3$  is the smallest eigenvalue of the normalised momentum tensor of the jets. It is designed to distinguish spherical events from planar or linear events, as SM particles originating from the decay of heavy particles tend to be collimated resulting in a more linear event shape [181].

$m(\text{RTj}), p_T(\text{RTj})$  are the mass and the transverse momentum of the reclustered jet as defined in Section 5.3, which can be used to target boosted topologies of heavy objects whose decay products become collimated in the direction of its boost.

$m_T(l, E_T^{\text{miss}})$  is the transverse mass of the lepton- $E_T^{\text{miss}}$  system used in the CR dedicated to the  $W$ +jets and Top background estimate (Section 7.9.1). It is defined from the lepton transverse momentum  $\mathbf{p}_T^l$  and the missing transverse momentum  $\mathbf{p}_T^{\text{miss}}$  as:

$$m_T = \sqrt{2p_T^l E_T^{\text{miss}}(1 - \cos(\Delta\phi(\mathbf{p}_T^l, \mathbf{p}_T^{\text{miss}})))} \quad (82)$$

## 6.4 OPTIMISATION METHODS

There are two methods to perform the Signal Region optimisation, following two slightly different strategies that lead to different event selections. The methods are the search for best discovery potential or for the strongest exclusion limits of the Signal Regions.

### 6.4.1 Best Discovery

The optimisation for the best discovery is primarily used the first time a dataset is studied, i.e. in the first iteration of a search with new data, when the upmost interest is clearly the discovery of physics beyond the Standard Model. The optimisation is done studying the power of rejection of the background-only (null) hypothesis,  $H_0$ , where the number of observed events is compatible with the number of expected events from SM processes only.

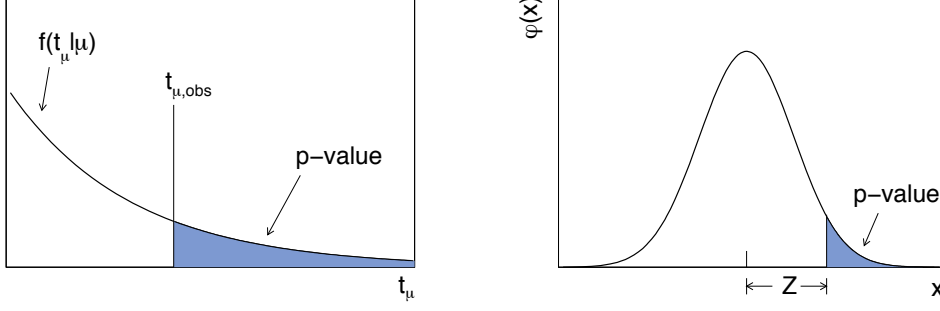


Figure 46: Illustration of the relation between the p-value obtained from an observed value of the test statistic  $t_\mu$ . The standard normal distribution shows the relation between the significance  $Z$  and the p-value. Figure is from [182].

If  $f(x|H_0)$  is the probability density function of having  $x$  events given the background-only hypothesis, the probability of observing  $x_{\text{obs}}$  is measured by the p-value:

$$p_0 = \int_{x_{\text{obs}}}^{\infty} f(x|H_0) dx \quad (83)$$

so that a low p-value is interpreted as bad agreement between hypothesis and observation. Usually a lower limit on the p-value,  $\alpha$  is chosen so that observation is defined in *critical* region if  $p \leq \alpha$ . If the number of observed events is not in agreement with the prediction, there is a possibility of a fluctuation. The p-value can be translated into the *significance* of the fluctuation,  $Z$ , which can be defined as the number of standard deviations  $\sigma$  that a Gaussian variable would fluctuate in one direction to give the same p-value, as illustrated in Figure 46:

$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx = 1 - \Phi(Z) \quad (84)$$

or alternatively:

$$Z = \Phi^{-1}(1 - p) \quad (85)$$

where  $\Phi$  is the cumulative Gaussian distribution function. The evidence for new physics is set by convention to be at  $Z \geq 3$ , while observation or discovery is defined at  $Z \geq 5$ . Therefore, having an observation with a significance of  $5\sigma$ 's means that the background-only hypothesis has a probability of  $\sim 3 \times 10^{-7}$ .

In the optimisation based on discovery potential, the goal is to find the combination of selection cuts that better rejects the background-only hypothesis,  $H_0$ , *given* an observation. If we expect  $b$  events from the background-only hypothesis and  $s$  events from the signal, the number of observed events is fixed at  $x_{\text{obs}} = s + b$ . The significance is then calculated with Eq.(85). Varying the combination of the variables and the values of the cuts, a signal region is chosen to cover a group of signal points representing a specific region of the parameter space.

### 6.4.2 Best Exclusion

The signal region optimisation method based on best exclusion limits differs from the previous in the hypothesis to be rejected. In the exclusion method the goal is to better reject the hypothesis concerning the presence of both the signal and the background,  $H_1$ , *given* an observation equal to the expected number of background events. The corresponding p-value is therefore defined as:

$$p_1 = p_{s+b} = \int_{x_{\text{obs}}}^{\infty} f(x|s+b) dx \quad (86)$$

and the hypothesis rejection is done by placing an upper limit on the signal using the  $CL_s$ -method [183]. The confidence level,  $CL_s$ , is defined as:

$$CL_s = \frac{p_1}{1 - p_0} \quad (87)$$

where  $p_0$  is already defined in Eq.(83) and  $p_1$  is defined in Eq. (86). Specifically, the  $\frac{1}{1-p_0}$  disfavors a downward fluctuation of the SM background.

By definition, if  $CL_s \leq 0.05$ , a signal model is excluded at 95% confidence level. An upper limit can be placed on the number of signal events by varying the signal strength in the  $H_1$  hypothesis, until  $CL_s$  reaches 0.05. Moreover, the provided expected-excluded number of signal events can be translated in an expected-excluded signal cross section,  $\sigma^{\text{exp}}$  for a certain integrated luminosity. This quantity is then used in the optimisation of the signal regions for best exclusion power by minimising the ratio:

$$\lambda = \frac{\sigma^{\text{exp}}}{\sigma_{\text{nom}}} \quad (88)$$

given the nominal cross section  $\sigma_{\text{nom}}$  for a given point of a SUSY model. The combinations resulting in the lowest value of  $\lambda$  for a larger part of the parameter space are chosen as the signal regions with the greatest exclusion power.

## 6.5 CONTROL REGIONS

The estimation of the number of events in each SR coming from the background processes is performed using a semi-data-driven procedure. For each of those backgrounds, a dedicated control region is defined with selections chosen such that the CR is enriched in one particular background and possibly depleted in signal events. On the other hand, CRs must be defined as close in phase space to the signal region as possible, otherwise the systematic error on the extrapolation would be too large. The balance between those two request is typically found by inverting or dropping one or two of the signal region cuts, and one or two additional criteria are imposed for each background. One signal region can have multiple control regions for different background processes.

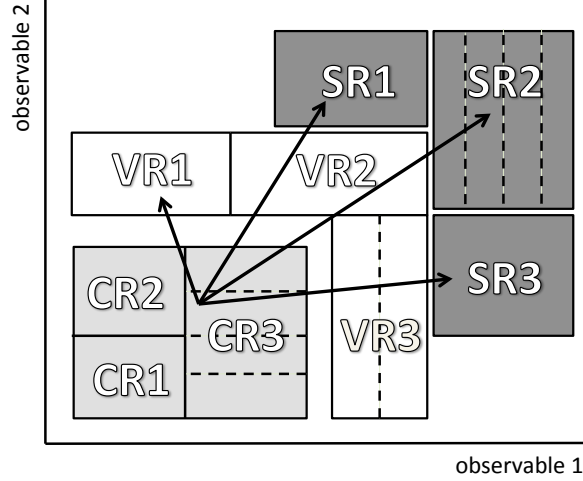


Figure 47: A schematic view of an analysis strategy with CRs, VRs and SRs. The extrapolation from the CRs to the SRs is verified in the VRs. The figure is taken from [184].

After the CRs definition, the contribution of the specific SM background to the signal region can be estimated by a simultaneous background fit in all CRs, given the fact that CRs are contaminated by other SM processes. This procedure assumes that the ratio of the yield in the CR to the yield in the SR is correct when using simulation. Such an assumption is then validated in Validation Regions.

For a given SM background process the ratio of the number of events in the SR and the number of events in the CR is assumed to be equal for the simulated (expected) events as for the events observed in data:

$$\frac{N_{\text{SR}}^{\text{data}}}{N_{\text{SR}}^{\text{MC}}} = \frac{N_{\text{CR}}^{\text{data}}}{N_{\text{CR}}^{\text{MC}}} \quad (89)$$

This allows to define *transfer factors* from the control region to the signal region and obtain the prediction for each background  $i$ . The transfer factor  $\text{TF}_{\text{CR} \rightarrow \text{SR}}$  is defined by rearranging Eq. (89) for each process:

$$N_{\text{SR}}^{\text{Est},i} = N_{\text{CR}}^{\text{data},i} \times \text{TF}_{\text{CR} \rightarrow \text{SR}} \quad (90)$$

### 6.5.1 Validation Regions

The background estimation procedure using control region is tested in dedicated *validation regions*. The VRs are built in order to test a specific selection cut used to define the control regions by reverting some of those cuts, i.e. re-implementing the SR cut. It is tested that a negligible amount of signal events enter into the VRs. A sketch of such a procedure is shown in Figure 47, where either the cut on variable 1 or variable 2 is reverted to define two VRs.

The fit result in the control regions is extrapolated to the VRs in the same way as to the SRs. This allows us to test our background

predictions in regions where no signal events are expected. The total estimated number of events in a validation region is found by adding the estimates of all the processes:

$$N_{\text{VR}}^{\text{Est}} = \sum_i N_{\text{CR}}^{\text{data},i} \times \frac{N_{\text{VR}}^{\text{MC},i}}{N_{\text{CR}}^{\text{MC},i}} \quad (91)$$

The use of the VRs is also fruitful to better investigate possible disagreements between expected and observed number of events that may arise before the signal region *unblinding*. As the signal contamination in VRs is expected to be low, those disagreements need to be understood in order to avoid possible false positives when data events are finally counted in the SRs.

## 6.6 STATISTICAL PROCEDURE

After the estimation of the number of expected events in the SRs and the CRs, the validity of the Standard Model hypothesis can be tested by comparing it with the number of observed events. Any excess over the expected background can be a sign of signal events in the signal region. If no excesses are reported, we can exclude specific hypotheses. In analyses devoted to the search for SUSY events, in case of no excesses, the results are upper limits on visible production cross sections of BSM physics and exclusions of specific hypotheses, e.g. of a SUSY simplified model.

The statistic analysis is based on likelihood functions. First, a fit with a profile likelihood function described in the Section 6.6.1, is used to obtain the expected number of background events in SRs. The profile likelihood function ensures that the cross-contamination between regions is automatically taken into account. Then, two hypothesis can be tested prediction in the SRs: the background-only (or *null*) hypothesis and the signal-plus-background hypothesis. The agreement of the observation with either hypothesis is quantified with a profile *log-likelihood-ratio* (LLR) [182] described in the Section 6.6.3.

### 6.6.1 The Likelihood Function

The likelihood function is defined for each signal region as the product of Poisson probability distributions of both the SRs and the corresponding CRs constraining the main backgrounds, and the Gaussian probability density functions constraining the systematic uncertainties, which are described by a set of nuisance parameters  $\theta$ :

$$L(\mathbf{n}|\boldsymbol{\mu}, \mathbf{s}, \mathbf{b}, \boldsymbol{\theta}) = P_{\text{SR}} \times \left( \prod_{i \in \text{CRs}} P_{\text{CR}_i} \right) \times C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) \quad (92)$$

In Eq. (92) each Poisson distribution function  $P_i \equiv P_i(n_i|\lambda_i(\boldsymbol{\mu}, \mathbf{s}_i, \mathbf{b}, \boldsymbol{\theta}))$  uses as input the observed number of events in the  $i$ -th region  $n_i$  and



the expected number of events in the  $i$ -th region  $\lambda_i$ . The latter is given by:

$$\lambda_i(\boldsymbol{\mu}, \mathbf{s}_i, \mathbf{b}, \boldsymbol{\theta}) = \mu_s \cdot s_i(\boldsymbol{\theta}) + \sum_j \mu_j \cdot b_{ij}(\boldsymbol{\theta}) + b_i^{VV}(\boldsymbol{\theta}) \quad (93)$$

where  $j$  sums over all the background processes.  $s_i(\boldsymbol{\theta})$ ,  $b_{ij}(\boldsymbol{\theta})$  are the expected number of signal and background events, respectively, in the  $i$ -th region taken from simulation, including the effect of the systematic uncertainty. The last term  $b_i^{VV}$  describes the diboson background, whose estimation in this analysis is taken directly from MC normalization and not using a transfer factor from a dedicated CR, as described later in Section 7.9.6. All the expected backgrounds and signal number of events can be multiplied with a normalisation factor  $\mu_{S(B)}$ . In the signal case,  $\mu_S$  is also called a *signal strength*, with  $\mu_S = 1$  corresponding to the un-normalised, expected yield of the signal, while  $\mu_S = 0$  is used when running a background or a discovery fit. In other fit types,  $\mu_S$  can be left free.

The systematic uncertainties are included using the probability density function  $C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta})$  where for each systematic  $\boldsymbol{\theta}$ , the nominal value to variate around is  $\boldsymbol{\theta}^0$ . By placing the dependence of the signal and background expectations on  $\boldsymbol{\theta}$  solely in the transfer factors, the term  $C_{\text{syst}}$  can be simplified by taking  $\boldsymbol{\theta}^0 = 0$  and normalising the individual constraint PDFs for  $\boldsymbol{\theta}$  appropriately. The effect of the systematic uncertainties on the expected number of events is described by the  $\mathbf{s}(\boldsymbol{\theta})$ ,  $\mathbf{b}(\boldsymbol{\theta})$  functions included in  $\lambda$ .  $C_{\text{syst}}$  is defined as a product of the Gaussian probability functions of the nuisance parameters, that parametrize the systematic uncertainties (SU):

$$C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) = \prod_{j \in \text{SU}} G(\boldsymbol{\theta}_j^0, \boldsymbol{\theta}_j) \quad (94)$$

### 6.6.2 Analysis Fits

There are three types of fits that are relevant in a search for BSM physics:

**Background-only** fit is used to obtain the expected number of background events in SRs. The fit is based on a likelihood function of the type in Eq.(92). The fit is performed using the observed event yields of the CRs associated with the SR as the only constraints, but not the yields of the SR itself. The fit is run under the assumption that no signal events from BSM physics contribute to these CR yields (i.e.  $\mu_S = 0$ ). The systematic and statistical uncertainties are included in the fit as nuisance parameters are constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties considered and by Poisson distributions, respectively. The background-only fit is also used to estimate the background event yields in the VRs.

**Model-Independent** fit is used to determine the agreement between expected and observed yield and to set upper limits on the number of BSM signal events in each signal region. Likewise the background-only fit, no potential signal contribution in the CRs is taken into account. On the other hand, the number of events observed in the signal region is added as an input to the fit. Moreover, the BSM signal strength, constrained to be non-negative, is added as a free parameter to the fit. The observed and expected upper limits at 95% confidence level (CL) on the number of events from BSM phenomena for each signal region may be interpreted as upper limits on the visible cross-section of BSM  $\langle\epsilon\sigma\rangle$ . The model-independent fit is also used to compute the one-sided p-value ( $p_0$ ) of the background-only hypothesis, which quantifies the statistical significance of an excess.

**Model-Dependent** fit is used to set exclusion limits on the signal cross-sections for specific SUSY models. In this case, signal contamination in the control regions is taken into account. Theoretical and experimental uncertainties on the signal production cross-section and kinematic distributions are also considered. Before inserting in the fit the observed number of events in a SR, the *expected* limit is found by calculating  $CL_s$  in each parameter point for each signal region only using simulation. Then, the SR providing the lowest expected  $CL_s$ -value is chosen to make the best expected limit and the same SR is used for that point for the observed limit. After the best SR for each parameter point is determined, the  $CL_s$ -value is calculated using the observed data. A parameter point is excluded if the calculated  $CL_s < 0.05$ . Once the procedure is done over all the points in the parameter space, an excluded area is drawn by triangular interpolation between the points. A typical exclusion limit plot for a SUSY search looks like sketched in Figure 48, where the red points are excluded and the area under the line is excluded.

The fits are performed using the HISTFITTER package [184], which relies on HISTFACTORY [185] and the ROOSTATS(ROOFIT) packages, based on the ROOT analysis framework [186].

### 6.6.3 Profile Log-Logarithmic Ratio

In order to quantify the compatibility of the observation with the hypothesis, a test-statistic  $q$  is constructed over a profile log-likelihood ratio:

$$LLR(\mu_S^*) = -2 \ln \left[ \frac{L(\mathbf{n}, \boldsymbol{\theta}^0 | \mu_S^*, \tilde{\mathbf{b}}, \tilde{\boldsymbol{\theta}})}{L(\mathbf{n}, \boldsymbol{\theta}^0 | \hat{\mu}_S, \hat{\mathbf{b}}, \hat{\boldsymbol{\theta}})} \right] \quad (95)$$

where the hatted symbols maximise the likelihood, while the tilded symbols are the best fitted values given a specific signal strength  $\mu_S^*$ .

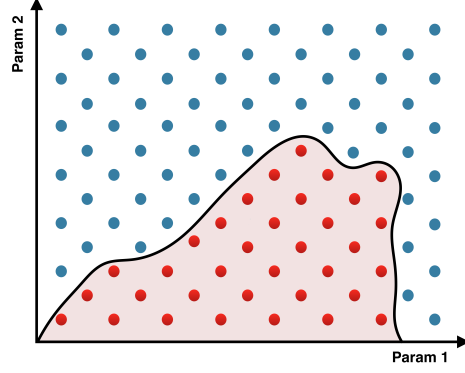


Figure 48: A sketch of a model dependent exclusion limit for a BSM model. The red dots are excluded up to 95% CL, while the blue are not excluded. The grey area represents the excluded part of the parameter space.

In case the best value for the signal strength is found to be negative, is put manually to  $\hat{\mu}_S$ .

The test-statistics for specific models is given by:

$$q_{\mu^*} = \begin{cases} \text{LLR}(\mu_S^*) & \text{if } \hat{\mu}_S \leq \mu_S^* \\ 0 & \text{if } \hat{\mu}_S > \mu_S^* \end{cases} \quad (96)$$

The fixed value of the statistics at zero represent the case of number of events below the expectations. The compatibility of the observations with the hypothesis is quantified by the  $p$ -value, already introduced in Section 6.4. Here is defined as:

$$p_{\mu_S^*} = \int_{q_{\text{obs}}}^{\infty} f(q_{\mu_S^*} | \mu_S^*) dq_{\mu} \quad (97)$$

where  $q_{\text{obs}}$  is the value of the test statistic observed in data and  $f(q_{\mu} | \mu)$  is the probability density function of the test statistic  $q$  given the signal strength  $\mu$ . An approximation with an asymptotic function [182] can be used to obtain the probability density function  $f$ , in case there are many event observed. Alternatively, a generation of toy dataset can be used if a SR is populated by few events (typically  $\leq 20$ ).

Upper limits on the number of signal events in a SR obtained with a model-independent exclusion fit can be subsequently used to obtain an upper limit on the production cross-section calculated per each parameter point via:

$$N = \sigma_{\text{TOT}} \times \mathcal{L}_{\text{int}} \times \epsilon \quad (98)$$

where  $\sigma_{\text{TOT}}$  is the production cross section for the sparticle (squarks, gluinos, etc.) and  $\epsilon$  is the reconstruction efficiency times acceptance of the signal point.



## SEARCH FOR SQUARKS AND GLUINOS IN FINAL STATES WITH JETS AND MISSING TRANSVERSE MOMENTUM AT $\sqrt{s} = 13 \text{ TeV}$

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In this thesis, we focus on the production of heavy SUSY particles that decay into final states without electrons or muons [187]. This analysis is very powerful in the search for R-parity conserving SUSY models in which squarks and gluinos can be produced in pairs ( $\tilde{g}\tilde{g}$ ,  $\tilde{g}\tilde{q}$ ,  $\tilde{q}\tilde{q}$ ) and may decay directly through  $\tilde{q} \rightarrow q\tilde{\chi}_1^0$  and  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  to weakly interacting lightest neutralinos, which is the lightest SUSY particle (LSP) and escapes the detector unseen. Alternatively, in other considered models sparticles can decay via the production of intermediate charginos as  $\tilde{q} \rightarrow q\tilde{\chi}_1^\pm$  and  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm$ . Subsequently, charginos decay to bosons as  $W^\pm\tilde{\chi}_1^0$ , leading to final states with larger multiplicities of jets.

In this chapter, a search for squark and gluino production in events with jets and missing transverse momentum (0-lepton) is presented. The analysis has been performed using the  $\sqrt{s} = 13 \text{ TeV}$  dataset collected by the ATLAS detector in 2015-2016. The results of the analysis can be found in [1]. It directly updates previous ATLAS results in  $\sqrt{s} = 13 \text{ TeV}$  [188] and previous version of the analysis performed at a collision energy of  $\sqrt{s} = 8$  and  $7 \text{ TeV}$  [3, 189].

As many analyses within ATLAS, the one presented here has been performed in a team of approximately 10 people. The author contribution to the analysis consists of several changes and improvements compared to previous versions:

- The determination of new dedicated final signal and control regions and the setting of exclusion limits on a set of simplified models with one-step decay of squarks and gluinos targeting various boosted bosons signatures. The SR definition takes advantage of new jet reclustering algorithm, whose relative uncertainties and their impact on the analysis sensitivity have been also studied by the author.
- The modelling and validation of baseline Monte Carlo signal samples comparing various combination of generators.
- The introduction of new SUSY signal models not previously considered by the 0-lepton analysis considering the presence of multiple bosons (W/Z/h) in final state, and the setting of the corresponding model dependent limits.
- The modeling and calculation of signal theory uncertainties with dedicated parametrization not yet considered.

Further contributions, being the author one of the main analyzers, lay in the development of the analysis framework used in this work and the maintenance thereof.

## 7.1 SUSY MODELS

SUSY signals are described using the simplified models [39, 40] which are defined by an effective Lagrangian describing the interactions of a small number of new particles, typically assuming one production process and one decay channel with a 100% branching fraction (see Section 2.5.2).

## 7.1.1 Simplified Models with Direct or One-Step Decays

Several SUSY models are considered in this analysis, describing strong pair-production of supersymmetric particles. Considered models imply squarks followed by direct ( $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ ) or one-step decays ( $\tilde{q} \rightarrow qW\tilde{\chi}_1^0$ ), and gluinos followed by direct ( $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ ) or one-step decays ( $\tilde{g} \rightarrow q\bar{q}'W\tilde{\chi}_1^0$ ,  $\tilde{g} \rightarrow q\bar{q}Z\tilde{\chi}_1^0$ ). Sketches of the production and decays are shown in Figure 49, 50, 51. These simplified models are defined such that all other superpartners except the lightest neutralino are decoupled, i.e. their mass is much higher.

The free parameters in the direct-decay models shown in Figure 49 are  $m_{\tilde{q}}$  or  $m_{\tilde{g}}$ , and  $m_{\tilde{\chi}_1^0}$ .

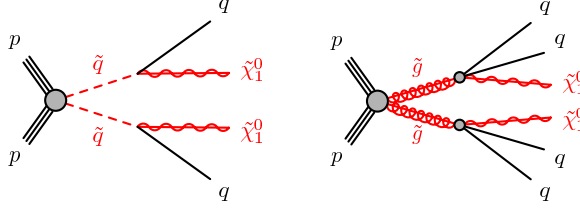


Figure 49: The decay topologies of squark-pair production (left) and gluino-pair production (right), in the simplified models with direct decays of squarks and direct decays of gluinos used in this note.

The one-step decay models shown in Figure 50 have two sets of free parameters:

- $m_{\tilde{g},\tilde{q}}$  and  $m_{\tilde{\chi}_1^0}$ , are varied and the mass of the chargino is fixed to  $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{g},\tilde{q}} + m_{\tilde{\chi}_1^0})/2$
- $m_{\tilde{g},\tilde{q}}$  and the parameter  $\kappa$ , defined as:

$$\kappa = \frac{\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}{\Delta m(\tilde{g}/\tilde{q}, \tilde{\chi}_1^0)} \quad (99)$$

are varied and  $m_{\tilde{\chi}_1^0} = 60$  GeV.

The latter case is investigated by the boosted analysis.

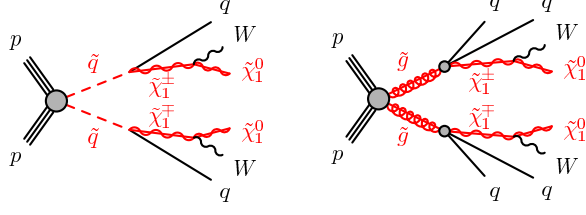


Figure 50: The decay topologies of squark-pair production (left) and gluino-pair production (right), in the simplified models with one-step decays of squarks and one-step decays of gluinos used in this note.

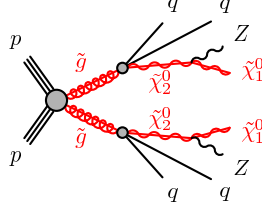


Figure 51: The decay topologies of gluino-pair production in the simplified model with Z in final state.

### 7.1.2 Simplified Models with W/Z/h Bosons in Final State

An additional set of SUSY signal, not previously considered for interpretation, is a simplified model with pair-produced gluino/squarks decaying to W/Z/h bosons with one-step decay via  $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$  (see Figure 52). The masses of  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^\pm$  are assumed to be equal and the mass of the  $\tilde{\chi}_1^0$  is fixed to 60 GeV. The minimum mass splitting  $\Delta m = m_{\tilde{\chi}_2^0 \text{ or } \tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  is set to be never less than 130 GeV. This ensures that  $\tilde{\chi}_2^0$  always decays through an on-shell Higgs and thus the branching ratios to W/Z/h bosons can be consistent throughout the whole signal grid. For gluino, BR of  $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^\pm$  and  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0$  decays are 50%, respectively. For squarks, BR of  $\tilde{q} \rightarrow q'\tilde{\chi}_1^\pm$  and  $\tilde{q} \rightarrow q\tilde{\chi}_2^0$  decays are 50%, respectively.  $\tilde{\chi}_1^\pm$  decays to a W boson and a  $\tilde{\chi}_1^0$  with 100% BR while  $\tilde{\chi}_2^0$  decays to  $Z\tilde{\chi}_1^0$  and  $h\tilde{\chi}_1^0$  at the equal rate.

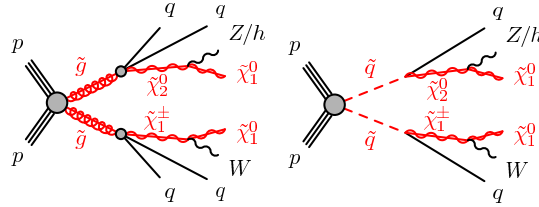


Figure 52: The decay topologies of gluino-pair (left) and squark-pair (right) production in the simplified model of W/Z/h in final state.

### 7.1.3 $pMSSM$

Phenomenological MSSM (pMSSM) like signal is also considered for interpretation. In this model, both gluino and light flavour squark productions are included, then, thanks to  $t, u$ -channel diagrams,  $\tilde{q}\tilde{\bar{q}}$  and  $\tilde{g}\tilde{g}$  production cross sections become larger than decoupled limits used in simplified models above. Moreover,  $\tilde{q}\tilde{\bar{q}}$  (or  $\tilde{\bar{q}}\tilde{q}$ ) and  $\tilde{q}\tilde{g}$  productions also exist with non-negligible cross sections. To simplify the model, only  $\tilde{\chi}_1^0$  is considered except for gluino and squarks. Other sparticles are assumed to be decoupled. The composition of  $\tilde{\chi}_1^0$  is assumed to be purely bino. Three values of  $\tilde{\chi}_1^0$  mass are considered:  $m_{\tilde{\chi}_1^0} = 0, 695, 995$  GeV.

## 7.2 STANDARD MODEL BACKGROUNDS

There are several SM processes that may mimic our signal in the final state with jets and missing transverse momentum. Some of the backgrounds have the same final state as the signal. Others arise from processes expected to have a different outcome, but resulting instead in the same final state as the signal because of phenomena like mis-identification of particles or mis-measurement of their energy.

Five SM background processes are mainly expected to contribute to the selection yield: Top ( $t\bar{t}$  and single-top),  $Z$ +jets,  $W$ +jets, diboson production and multijet events from strong interactions.

### 7.2.1 *Top*

Top quarks-pair production can occur via  $q\bar{q} \rightarrow t\bar{t}$  or gluon fusion  $gg \rightarrow t\bar{t}$ . The latter is the dominant mechanism at the LHC, as anti-quarks are only available at sea level. Due to its short lifetime, top quarks decay before hadronizing predominately into a  $W$  boson and a  $b$  quark.

A produced  $t\bar{t}$  pair decays fully hadronically, semileptonically or dileptonically.

In the case of semileptonic and dileptonic decays, the top decay to taus  $\tau\bar{\nu}_\tau$ , subsequently decaying to hadrons ("hadronic taus"), is the most dominant contribution. The hadronic taus have very similar kinematic to jets and can be therefore mis-identified. Semileptonic, and with even lower probability dileptonic decays are instead less favoured and play a role when the lepton is mis-identified as a jet or the lepton is not reconstructed as it may be outside of the detector acceptance, so that jets and real  $E_T^{\text{miss}}$  from the  $\nu_l$  will be present in the final state.

A hadronic decay of the top quark  $t \rightarrow b q \bar{q}'$  will lead to fake  $E_T^{\text{miss}}$  when the energy of the jet is mis-measured, a case accounted in the multijet background (Section 7.2.4).

$t\bar{t}$  production in association with EW processes ( $t\bar{t} + W/Z/WW$ ) are also considered as contributing to the Top background.



Single-top production occurs through a s-channel or t-channel diagrams, or in association with a  $W$  boson. The top quark decays into  $Wb$  and forms a background for the same reasons as the  $t\bar{t}$  pairs.

All other backgrounds, e.g. the  $t\bar{t}$  association production with a Higgs boson, are negligible due to either their very small cross-section or the event selection.

### 7.2.2 Vector Boson + Jets

$W$  bosons decay either hadronically (67.6%) or leptonically (10.8% per flavour). The production of a  $W$  boson can occur with associated jets making the cross-section decrease of  $\sim 1/\alpha_S$  with each additional jet. The main background contribution comes from  $W$  decaying to hadronic taus or  $e/\mu$  misidentified as jets.

$Z$  bosons can decay invisibly to neutrinos so that the  $Z(\rightarrow \nu\bar{\nu})$ +jets process is one of the largest background for the study, especially in signal regions with low jet multiplicity. As the signature cannot be discerned from a supersymmetrical event with same final state, the background is irreducible.  $Z(\rightarrow \tau\bar{\tau})$ +jets with hadronic taus is a background as well, but the branching fraction is much lower than for the invisible decay.

### 7.2.3 Diboson

Diboson production can occur as  $ZZ, WW, WZ, W\gamma, Z\gamma$ . It can produce similar final state as for our signals. If a  $Z$  decays into neutrinos and a  $W$  or  $Z$  decays hadronically, the final state will show real  $E_T^{\text{miss}}$  from neutrinos and jets. The  $W$  can also decay leptonically, the lepton being unidentified.

### 7.2.4 Multijets

The multijets background is caused by the QCD multijet production through the strong interactions occurring in  $pp$  collisions at the LHC. The two-parton interactions can result in high- $p_T$  dijet events, in which the emission of hard gluons can result in additional jets. Multijet processes have high cross section but do not contain real  $E_T^{\text{miss}}$ . Unidentification of jets, possibly lost in crack regions of the detector, or more frequently jet-energy mismeasurement can lead to fake  $E_T^{\text{miss}}$ , which is usually aligned with one of the jet.

Multijets events can also arise from heavy-flavour interactions, in the case of  $b$ -quarks produced in the  $pp$  collision decay semileptonically. The leptons from  $b$ -fragmentation tend to be close to jets, i.e they do not fulfill isolation requirements causing the lepton to be potentially mis-identified as a jet, again resulting in high- $p_T$  jets and real  $E_T^{\text{miss}}$ .

The multijet background yield is the only one estimated solely by using a data-driven technique.

### 7.3 MONTE CARLO SAMPLES

Monte Carlo samples are used to obtain background predictions via the use of transfer factors, defined in Eq. (89), and to assess the sensitivity to various SUSY models. Samples for SM processes are produced using the full simulation of the ATLAS detector [136], while signal samples were prepared using a fast simulation of the detector [138] based on a parametrization of the performances of the ATLAS calorimetric system.

A summary of the generators used for event generation and parton showering, the order in the strong coupling,  $\alpha_s$ , of the cross section calculation and eventual precision in re-summation of soft gluon emission, the Monte Carlo generator tune, and the PDF set for each background sample are given in Table 7.

#### 7.3.1 Signal Samples

Signal samples of the simplified models used in this work are generated at the matrix element level with MG5\_AMC@NLO [132] interfaced to PYTHIA 8 [127] for the parton showering and fragmentation. The generator setup is named M5P8. The A14 [120] set of tuned parameters (tune) was used for initial/final-state radiation (ISR/FSR) and underlying-event parameters together with the NNPDF2.3LO [110] parton distribution function (PDF) set. The signal cross sections are calculated at NLO in  $\alpha_s$ , with re-summation of soft gluon emission to NLL accuracy [190, 191, 192]. Only light-flavour quarks squarks ( $\tilde{d}$ ,  $\tilde{u}$ ,  $\tilde{c}$ ,  $\tilde{s}$ ) are considered.

Simplified models with direct decay of squarks and pMSSM models assume an eightfold degeneracy on the first two generation squark masses. Simplified models with one-step decay of squarks assume a fourfold degeneracy.

In simplified models with  $\tilde{q}\tilde{q}$  ( $\tilde{g}\tilde{g}$ ) pair production, the gluino (squark) is assumed to have mass of  $m_{\tilde{g}(\tilde{q})} = 45$  TeV in the cross section calculation, i.e. to be decoupled and beyond the reach of the LHC.

#### 7.3.2 Background Samples

##### *Vector Boson Samples*

The vector boson production in association with jets is simulated using SHERPA [102] event generator, version 2.2.1, with matrix elements calculation up to 2 partons at NLO and up to two additional partons at leading order (LO) using the COMIX [193] and OPEN LOOPS [194] matrix-element generators, and merged with the SHERPA parton shower [195] using the ME+PS@NLO prescription [196]. Events with  $\gamma$ +jets were generated requiring  $p_T^\gamma > 35$  GeV. For these events, matrix elements were calculated at LO with up to three or four partons depending on the  $p_T$  of the photon, and merged with the CSHERPA parton shower using the ME+PS@LO prescription [197]. The  $W/Z$ +jets events were

normalized using their NNLO cross sections [198], while the  $\gamma$ +jets LO cross section, taken directly from the SHERPA-1.4.0 MC event generator, was multiplied by a correction factor as described in Section 7.9.6.

### *Top Samples*

The  $t\bar{t}$  and single-top processes in the  $Wt$  and s-channel [199], are generated with the POWHEG-BOX v2 [135] generator, while electroweak (EW) t-channel single-top events were modeled using POWHEG-BOX v1<sup>1</sup>. For each process the top quark mass was set to 172.5 GeV<sup>2</sup>. The generator is then interfaced with PYTHIA 6.428 [126] for fragmentation, using the CTEQ6L1 [111] PDF set and the corresponding PERUGIA 2012 tune (P2012) [201].

The  $t\bar{t}$  events were normalized to cross sections obtained from NNLO QCD calculations including NNLL [202, 203] accuracy, while s- and t-channel single-top events were normalized to the NLO cross sections [204, 205], and the  $Wt$ -channel single-top events were normalized to the NNLO+NNLL cross sections [206, 207]. Production of a top quark in association with a Z boson is generated with the MG5\_aMC@NLO 2.2.1 generator at LO with CTEQ6L1 PDF set. Other minor top processes are also included in the resume Table 7.

### *Diboson Samples*

Diboson processes ( $WW$ ,  $WZ$ ,  $ZZ$ ) [208] were simulated using the SHERPA 2.1.1 generator. For processes with four charged leptons ( $4\ell$ ), three charged leptons and a neutrino ( $3\ell+1\nu$ ) or two charged leptons and two neutrinos ( $2\ell+2\nu$ ), the matrix elements contain all diagrams with four electroweak couplings, and were calculated for up to one ( $4\ell$ ,  $2\ell+2\nu$ ) or no partons ( $3\ell+1\nu$ ) at NLO. For processes in which one of the bosons decays hadronically and the other leptonically, matrix elements were calculated for up to one ( $ZZ$ ) or no ( $WW$ ,  $WZ$ ) additional partons at NLO. All diboson samples also simulated up to three additional partons at LO using the COMIX and OPENLOOPS matrix-element generators, and were merged with the SHERPA-1.4.0 parton shower using the ME+PS@NLO prescription. Triboson processes ( $WWW$ ,  $ZZZ$ ,  $WWZ$ ) are not used in this analysis as they are considered to contribute negligibly.

#### 7.3.3 *Pile-up Reweighting*

The pile-up, i.e. the multiple proton-proton interactions per bunch crossing, has to be included in the simulation as it can affect the reconstruction efficiencies. Events in the simulation samples are overlaid with soft QCD processes generated with PYTHIA 8.186 [127], to emulate multiple pp collisions.

<sup>1</sup> POWHEG-BOX v1 generator uses the four-flavor scheme for the NLO matrix-element calculations together with the fixed four-flavor PDF set CT10f4 [200]

<sup>2</sup> The resummation damping factor  $h_{\text{damp}}$ , which is one of the parameters controlling the ME/PS matching in POWHEG, and effectively regulating the high- $p_T$  radiation against which the  $t\bar{t}$  system recoils, was set to the top quark mass.

Table 7: The SUSY signals and the Standard Model background Monte Carlo simulation samples used in this analysis. The generators, the order in  $\alpha_s$  of cross section calculations used for yield normalization, PDF sets, parton showers and the underlying event tunes are shown. "P" stands for PYTHIA, "MG5" stands for MG5\_AMC@NLO.

| Physics process                                      | Generator     | Cross-section normalization | PDF set      | PS+ Frag. | Tune           |
|------------------------------------------------------|---------------|-----------------------------|--------------|-----------|----------------|
| SUSY processes                                       | MG5 2.2.2-3   | NLO+NNL                     | NNPDF2.3LO   | P8.186    | A14            |
| $W(\rightarrow \ell\nu)+\text{jets}$                 | SHERPA 2.2.1  | NNLO                        | NNPDF3.0NNLO | SHERPA    | SHERPA DEFAULT |
| $Z/\gamma^*(\rightarrow \ell\bar{\ell})+\text{jets}$ | SHERPA 2.2.1  | NNLO                        | NNPDF3.0NNLO | SHERPA    | SHERPA DEFAULT |
| $\gamma + \text{jets}$                               | SHERPA 2.1.1  | LO                          | CT10         | SHERPA    | SHERPA DEFAULT |
| $t\bar{t}$                                           | POWHEG-Box v2 | NNLO+NNLL                   | CT10         | P6.428    | PERUGIA2012    |
| $Wt$ -channel                                        | POWHEG-Box v2 | NNLO+NNLL                   | CT10         | P6.428    | PERUGIA2012    |
| $s$ -channel                                         | POWHEG-Box v2 | NLO                         | CT10         | P6.428    | PERUGIA2012    |
| $t$ -channel                                         | POWHEG-Box v1 | NLO                         | CT10f4       | P6.428    | PERUGIA2012    |
| $t\bar{t} + W/Z/WW$                                  | MG5 2.2.3     | NLO                         | NNPDF2.3LO   | P8.186    | A14            |
| $WW, WZ, ZZ$                                         | SHERPA 2.1.1  | NLO                         | CT10         | SHERPA    | SHERPA DEFAULT |

The pile-up re-weighting is applied on the MC samples which were generated with a rather flat distribution in number of additional  $pp$  interactions<sup>3</sup>, in order to match the distribution of the average number of interactions to that observed in data.

The systematic uncertainty on the re-weighting is evaluated by changing the scale factor from 1 (*up* variation) to 1/1.18 (*down* variation).

## 7.4 DATASET AND TRIGGER

### 7.4.1 Dataset

The dataset used in the analysis was collected by the ATLAS detector during 2015 and 2016 from proton-proton collisions produced at the LHC at a collision energy of  $\sqrt{s} = 13$  TeV, with a 25 ns bunch spacing. The average number of  $pp$  collisions per bunch crossing was  $\langle\mu\rangle = 14$  in 2015 and  $\langle\mu\rangle = 24$  in 2016. Events are required to pass a Good Run List (GRL), ensuring that all the sub-detectors of ATLAS were in good conditions and delivering high quality data. The resulting total integrated luminosity is  $36.1 \text{ fb}^{-1}$ . The uncertainty on luminosity is 3.2%, obtained by a method similar to the one described in Ref [209]

### 7.4.2 Trigger

The trigger system of ATLAS at the time of Run2 data-taking consists of two layers, a hardware trigger L1, and a higher level software trigger HTL. The dataset used in the search was selected by triggering on

<sup>3</sup> Simulations are usually produced prior the data taking, simulating an average pile-up  $\langle\mu\rangle$  in a certain range. However, before the data taking the exact distribution of  $\langle\mu\rangle$  is not known.

events with  $E_T^{\text{miss}} > 70$  GeV at HLT trigger level for the data collected in 2015 or above 90-110 GeV, depending on data taking period for data collected in 2016.

Additional triggers are used in control regions using  $e, \mu, \gamma$ .

In the CRY, `HLT_g120_loose(HLT_g140_loose)` is used for the dataset of 2015(2016) to select photons with  $E_T^{\text{miss}} > 120(140)$  GeV.

In the CRW, CRT, CRZ, events are required to pass a more sophisticated trigger logic for  $e, \mu$ .

In the CRQ, single-jet trigger are used.

### $E_T^{\text{miss}}$ -Trigger Efficiencies

The missing transverse momentum used by the trigger is not fully calibrated and a cut tighter than the thresholds above is needed to ensure that the trigger is 100% efficient for the event selection considered in the analysis.

To emulate online- $E_T^{\text{miss}}$ , where no muon momentum is considered in calorimetric-based  $E_T^{\text{miss}}$ , the muon contribution is subtracted from the offline- $E_T^{\text{miss}}$  calculation. A plateau for  $E_T^{\text{miss}} > 200$  GeV is observed in the turn-on curves for the trigger efficiency estimation, as shown in Figure 53.

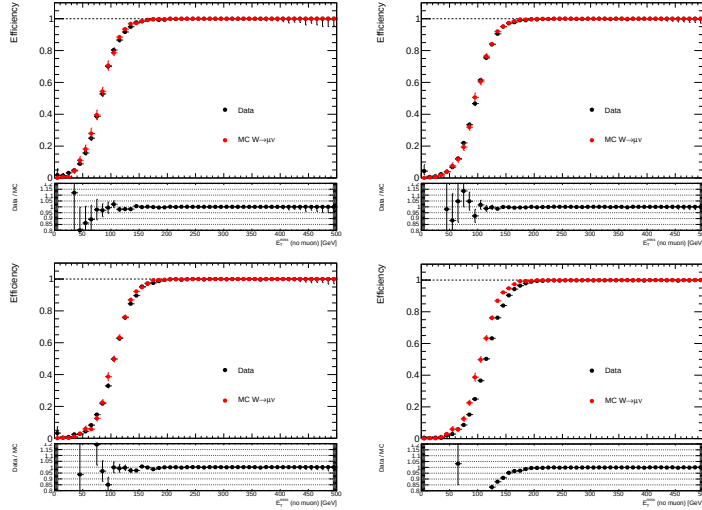


Figure 53:  $E_T^{\text{miss}}$ -trigger efficiency for various data taking periods, compared with MC simulation ( $W \rightarrow \mu\nu + \text{jets}$ ) as a function of  $E_T^{\text{miss}}$  without muon term. `HLT_xe70_mht` (upper left), `HLT_xe90_mht_L1XE50` (upper right), `HLT_xe100_mht_L1XE50` (lower left) and `HLT_xe110_mht_L1XE50` (lower right). In the plot of `HLT_xe110_mht_L1XE50`, `HLT_xe100_mht_L1XE50` is used for MC.

## 7.5 OBJECT DEFINITION

The reconstruction and identification of the physics objects used in this analysis are defined in Chapter 5. However, additional offline criteria are used before defining the set of cuts implemented in the signal regions.

Two different classes, *baseline* and *high-purity*, are defined for leptons (electrons or muons) and photons. The baseline leptons are used in the removal of overlapping objects and to veto leptons in the signal regions. The baseline photons are used to remove the overlap with leptons and with jets. The high-purity leptons are used in selecting events in the control regions dedicated to estimating residual W+jets and Top backgrounds. The high-purity photons are used in selecting  $\gamma$ +jets events in the control region dedicated to the Z+jets background estimation.

A summary of the cuts used to define the objects are given in Table 8. Here follows a short description for each physics object used in the analysis:

**Jets** candidates are reconstructed using the Anti- $k_t$  clustering algorithm [151] with a jet radius parameter of 0.4 starting from clusters of calorimeter cells [150]. All jets used in the removal of overlapping objects are required to have  $p_T > 20$  GeV and  $|\eta| < 2.8$ . To suppress jets from pileup events, the requirement of  $JVT > 0.59$ , where JVT is defined in Section 5.2.2, is only applied to jets with  $20 < p_T < 60$  GeV and  $|\eta| < 2.4$ .

**b-tagging** algorithm based on boosted decision trees, MV2c10 [162, 163], is used to identify jets containing a b-hadron. They have to pass the 77% efficiency working point of the fixed cut of the algorithm and they are required to have  $p_T > 50$  GeV and to lie within  $|\eta| < 2.5$ .

**large-R Jets** Initial jet-finding is extended using an approach called jet re-clustering [160], as described in Section 5.3.

**Electrons** Baseline electron candidates are reconstructed as described in Section 5.5.1 from an isolated EM energy deposit matched to an ID track and are required to have  $p_T > 7$  GeV and to lie within  $|\eta| < 2.47$ , and to satisfy *Loose* ID requirements described in [166]. High-purity electron candidates additionally must satisfy *Tight* selection criteria described [166], and the leading electron must have  $p_T > 27$  GeV.

**Muons** Baseline muon candidates are reconstructed as described in Section 5.6 by combining information from the muon spectrometer and inner tracking detectors as described in Ref. [175], and are required to have  $p_T > 7$  GeV and to lie within  $|\eta| < 2.7$ . High-purity muons must additionally have  $|\eta| < 2.4$  and to satisfy *Gradient-Loose* isolation requirements described in Ref. [175].

**Photons** candidates are required to satisfy  $p_T > 150$  GeV and  $|\eta| < 2.37$ , photon shower shape and electron rejection criteria, and to be isolated as described in ref. [172]. Ambiguities between leptons

|                    |                                                          |  |                                                                                               |
|--------------------|----------------------------------------------------------|--|-----------------------------------------------------------------------------------------------|
| <b>Jets</b>        |                                                          |  | Signal                                                                                        |
| Acceptance         |                                                          |  | $p_T > 20 \text{ GeV}$ and $ \eta  < 2.8$                                                     |
| Pileup suppression |                                                          |  | $p_T > 60 \text{ GeV} \parallel (p_T > 20 \text{ GeV} \ \& \  \eta  < 2.8 \ \& \ JVT > 0.59)$ |
| <b>b-Jets</b>      |                                                          |  | Signal                                                                                        |
| algorithm          |                                                          |  | MV2c10 at 77% efficiency point                                                                |
| Acceptance         |                                                          |  | $p_T > 50 \text{ GeV}$ and $ \eta  < 2.5$                                                     |
| <b>RT-jets</b>     |                                                          |  | Signal                                                                                        |
| Algorithm          |                                                          |  | anti-kt, $R = 1.0$                                                                            |
| Input              |                                                          |  | Baseline jets with $p_T > 20 \text{ GeV}$                                                     |
| <b>Electrons</b>   |                                                          |  | Baseline                                                                                      |
| Acceptance         | $p_T > 7 \text{ GeV}$ and $ \eta^{\text{clust}}  < 2.47$ |  | High-Quality                                                                                  |
| Quality            | LooseLH                                                  |  | $p_T > 7 \text{ GeV}$                                                                         |
| Overlap            | $\Delta R(e, \text{jet}) > 0.4$                          |  | TightLL                                                                                       |
| Isolation          | -                                                        |  | $\Delta R(e, \text{jet}) > 0.4$                                                               |
| Track              | -                                                        |  | GradientLoose                                                                                 |
|                    |                                                          |  | $ z_0^{\text{PV}} \cdot \sin\theta  < 0.5 \text{ mm}$                                         |
|                    |                                                          |  | $ d_0^{\text{PV}} /\sigma(d_0^{\text{PV}}) < 5$                                               |
| <b>Muon</b>        |                                                          |  | Baseline                                                                                      |
| Acceptance         | $p_T > 7 \text{ GeV}$ and $ \eta  < 2.7$                 |  | High-Quality                                                                                  |
| Quality            | Medium                                                   |  | $p_T > 7 \text{ GeV}$                                                                         |
| Overlap            | $\Delta R(\mu, \text{jet}) > 0.4$                        |  | Medium                                                                                        |
| Isolation          | -                                                        |  | $\Delta R(\mu, \text{jet}) > 0.4$                                                             |
| Track              | -                                                        |  | GradientLoose                                                                                 |
|                    |                                                          |  | $ z_0^{\text{PV}} \cdot \sin\theta  < 0.5 \text{ mm}$                                         |
|                    |                                                          |  | $ d_0^{\text{PV}} /\sigma(d_0^{\text{PV}}) < 3$                                               |
| <b>Photon</b>      |                                                          |  | Baseline                                                                                      |
| Acceptance         | $p_T > 25 \text{ GeV}$ and $ \eta  < 2.37$               |  | High-Quality                                                                                  |
| Quality            | Loose                                                    |  | -                                                                                             |
| Overlap            | $\Delta R(\gamma, \text{jet}) > 0.4$                     |  | Tight                                                                                         |
| Isolation          | -                                                        |  | $\Delta R(\gamma, \text{jet}) > 0.4$                                                          |
|                    |                                                          |  | FixedCutTight                                                                                 |

Table 8: The cuts used to define the physics objects in the analysis.

and photons are removed by requiring the photon to be discarded if it lies between  $\Delta R \leq 0.4$  of a baseline electron or muon.

## 7.6 EVENT PRESELECTION

All the signal regions undergo a common *preselection*, after which the final event selection of each signal region is found by optimization. The event preselection includes event cleaning, cuts on  $E_T^{\text{miss}}$  and  $p_T$  of the leading jets and cuts to reject multijet background.

### 7.6.1 Event Cleaning

The event cleaning procedure employs selection cuts used to reject events where the detector response is not coming solely from  $pp$  col-

lisions, but is contaminated by cosmic rays, discharges in the detector, beam remnants, and objects pointing to problematic detector regions.

#### *Non-collision Background*

Non-collision background (NCB) events come from different sources than  $pp$  collisions, such as cosmic ray events, beam-gas or calorimetric noise. Those events can lead to fake or real energy deposits in the calorimeter, which may eventually be reconstructed as jets. As the statistics gets larger, more NCB events can be seen. Jet properties can be used to discriminate background jet candidates not originating from hard scattering processes. Events with a jet with  $p_T > 20$  GeV failing to satisfy the **LooseBad** requirements, or events with at least one of the two leading jets with  $p_T > 100$  GeV failing to satisfy the **TightBad** quality criteria (both defined in Ref. [210]), are rejected. Those requirements are based on the fraction of the  $p_T^{\text{tracks}}$  to the total energy of the jet, and the maximal fraction of an energy deposit in a single layer of the calorimeter.

The jet *time*, which is defined as the energy weighted average of the cell time is also used in the NCB estimation. Out-of-time jets is indicative of non-collision energy deposits. Events where the energy weighted time of the first two leading jets is larger than 4 ns are rejected.

#### *Problematic Regions in the Calorimeter*

In the 2015 data, dead Tile regions have been found, situated at ( $0 < \eta < 0.9$  and  $\phi = 0.9$ ), and at ( $-1.6 < \eta < -0.9$  and  $\phi = 2.0$ ). Dead cells can cause mis-measurement of the  $E_T^{\text{miss}}$  if the jet is pointing in the direction of the dead regions. In order to reject the influence of the dead Tile region on the selection quality, a specific dead Tile *veto* has been set in signal region and multijet control regions. The veto is rejecting jets lying in the dead Tile regions and with  $p_T > 50$  GeV and  $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}}) < 0.3$ . This cut is applied only for 2015 data since there is no dead Tile region in 2016.

#### *Misidentified Muons*

Reconstructed muons not originating from the  $pp$  collisions, referred to as *fake* muons, can cause large fake- $E_T^{\text{miss}}$ . There can be diverse origins of the fake muons, such as high hit multiplicities in the muon spectrometer coming from jets punching through the calorimeter into the muon system, or badly measured inner detector tracks in jets wrongly matched to muon spectrometer segments, and others. In order to discriminate events with fake muons, events containing muons are rejected if muons are not originating from the primary vertex, i. e. a muon with  $|z_0^{\text{PV}}| > 1$  mm or  $|d_0^{\text{PV}}| > 0.2$  mm after overlap removal. Moreover, events with  $\frac{(E_T^{\text{miss}})^{\text{muon}}}{E_T^{\text{miss}}} \cdot \cos(\Delta\phi((\vec{E}_T^{\text{miss}})^{\text{muon}}, \vec{E}_T^{\text{miss}})) > 0.5$  are rejected, in order to clean from large- $E_T^{\text{miss}}$  events due to badly reconstructed muons. Since the analysis searches for new physics with no lepton in



the final state, the inefficiency of these cuts is negligible. This cut is only applied to signal region and not in other control regions.

| GRL                                          | default                                                     |
|----------------------------------------------|-------------------------------------------------------------|
| Primary vertex                               | Leading primary vertex with at least one track              |
| Lepton                                       | No selected lepton after overlap removal with $p_T > 7$ GeV |
| $E_T^{\text{miss}}$                          | $> 250$ GeV                                                 |
| $p_T(j_1)$                                   | $> 200$ GeV                                                 |
| $p_T(j_2)$                                   | $> 50$ GeV                                                  |
| $\Delta\phi(j_{1,2,(3)}, E_T^{\text{miss}})$ | $> 0.4$                                                     |
| $m_{\text{eff}}(\text{incl.})$               | $> 800$ GeV                                                 |

Table 9: Signal region-like preselections to check cleaning cut efficiency.

### 7.6.2 Preselection

After applying the cleaning cuts dedicated to specific sources of background events, some minimum requirements on the analysis discriminating variables are placed. The preselections for the various topologies considered in this work are described in Table 9.

#### $E_T^{\text{miss}}$ and $Jet\text{-}p_T$

The minimum requirement on the  $E_T^{\text{miss}}$  is motivated by the trigger threshold described in Section 7.4.2. In order for the trigger to be fully efficient, the missing transverse momentum must be larger than 250 GeV. All events in the signal regions must contain at least 2 jets, where the most energetic jet must have  $p_T > 200$  GeV, while the subleading jet must have  $p_T > 50$  GeV.

#### Lepton Veto

The analysis described in this work is selecting events in final states with jets and missing transverse momentum, and no leptons. Therefore, a veto on events with any baseline muons or electrons after overlap removal is placed to reject  $W(\rightarrow l\nu)+\text{jets}$  and leptonic  $t\bar{t}$  events in which neutrinos generate the  $E_T^{\text{miss}}$  signature. The lepton  $p_T$  threshold used in the veto is set at 7 GeV for both electrons and muons.

## 7.7 EVENT SELECTION

After the composition of both dataset of simulated and detected events, and the event preselection, we can proceed to set various selection cuts to classify events as background-like, for the control regions, or signal-like, for the signal regions. The signal regions are all optimised to cover the largest area of discovery or exclusion potential in the parameter space of the simplified models, following the method described in Section 6.4. In order to maximise the sensitivity, five jet multiplicities (from 2 to 6 jets) are used in this analysis in order to be sensitive to a range of models. The signal regions are named after the jet multiplicities and the increasing cut on the effective mass  $m_{\text{eff}}$  discriminating variable, introduced in Section 6.3.

Twenty-two inclusive SRs are defined in Table 10. The first block of SRs targets the  $\tilde{q}\tilde{q}$  direct decay simplified models shown in Figure 49 (left), the second block of SRs targets the  $\tilde{g}\tilde{g}$  direct decay simplified models shown in Figure 49 (right). The third block of SRs targets the one-step decay simplified models in Figures 50 (left) and 50 (right).

In each region different thresholds are applied on jet  $p_T$  and jet  $\eta$ . These thresholds are defined to reduce SM background while keeping high selection efficiency for the targeted signals which tend to have harder jets in the central region.

The suppression of the QCD events is performed exploiting the kinematic of the multijet background. In events with fake  $E_T^{\text{miss}}$ , the angle between the jets momentum and the direction of the missing trasverse momentum,  $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\min}$ , is usually low since the two vectors tend to have the same directions, while in events with real missing transverse momentum, such as the SUSY events searched for,  $E_T^{\text{miss}}$  has recoiled against an object. For the 2-jet SRs optimized for  $\tilde{q}\tilde{q}$  pair production followed by direct decay, and for signal region 5j-2600, the selection requires  $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} > 0.8$ , using up to three leading jets (if present in the event), while in SRs with higher jet multiplicities the requirement  $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} > 0.4$  is used. For the higher jet multiplicities, an additional requirement on  $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\min} > 0.4$  (or  $> 0.2$ ) is imposed on the remaining jets.

The further selection to better reject QCD events and discriminate it against the signal, is based on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$  (called the  $E_T^{\text{miss}}$ -significance). Since additional jets in a SUSY event decrease the probability of having an LSP with high momentum, resulting then in high  $E_T^{\text{miss}}$ , the selection on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  tend to decrease with increasing jet multiplicity. Furthermore, the requirement on  $E_T^{\text{miss}}/\sqrt{H_T}$  is used in several two- and four-jet regions, since the variable is found to provide enhanced sensitivity to models with  $\tilde{q}\tilde{q}$  pair production.

| Targeted signal                                                      | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ |         |         |         |         |         |         |         |
|----------------------------------------------------------------------|---------------------------------------------------------------|---------|---------|---------|---------|---------|---------|---------|
| Requirement                                                          | Signal Region [Meff-]                                         |         |         |         |         |         |         |         |
|                                                                      | 2j-1200                                                       | 2j-1600 | 2j-2000 | 2j-2400 | 2j-2800 | 2j-3600 | 2j-2100 | 3j-1300 |
| $E_T^{\text{miss}} \text{ [GeV]} >$                                  | 250                                                           |         |         |         |         |         |         |         |
| $p_T(j_1) \text{ [GeV]} >$                                           | 250                                                           | 300     | 350     |         |         |         | 600     | 700     |
| $p_T(j_2) \text{ [GeV]} >$                                           | 250                                                           | 300     | 350     |         |         |         | 50      |         |
| $p_T(j_3) \text{ [GeV]} >$                                           | –                                                             |         |         |         |         |         |         | 50      |
| $ \eta(j_{1,2})  <$                                                  | 0.8                                                           | 1.2     |         |         |         | –       |         |         |
| $\Delta\Phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} >$ | 0.8                                                           |         |         |         |         |         | 0.4     |         |
| $\Delta\Phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\min} >$     | 0.4                                                           |         |         |         |         |         | 0.2     |         |
| $E_T^{\text{miss}}/\sqrt{H_T} \text{ [GeV}^{1/2}] >$                 | 14                                                            | 18      |         |         |         |         | 26      | 16      |
| $m_{\text{eff}}(\text{incl.}) \text{ [GeV]} >$                       | 1200                                                          | 1600    | 2000    | 2400    | 2800    | 3600    | 2100    | 1300    |

| Targeted signal                                                      | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ |         |         |         |         |         |         |    |
|----------------------------------------------------------------------|----------------------------------------------------------------------|---------|---------|---------|---------|---------|---------|----|
| Requirement                                                          | Signal Region [Meff-]                                                |         |         |         |         |         |         |    |
|                                                                      | 4j-1000                                                              | 4j-1400 | 4j-1800 | 4j-2200 | 4j-2600 | 4j-3000 | 5j-1700 |    |
| $E_T^{\text{miss}} \text{ [GeV]} >$                                  | 250                                                                  |         |         |         |         |         |         |    |
| $p_T(j_1) \text{ [GeV]} >$                                           | 200                                                                  |         |         |         |         |         | 700     |    |
| $p_T(j_4) \text{ [GeV]} >$                                           | 100                                                                  |         |         |         | 150     |         | 50      |    |
| $p_T(j_5) \text{ [GeV]} >$                                           | –                                                                    |         |         |         |         |         |         | 50 |
| $ \eta(j_{1,2,3,4})  <$                                              | 1.2                                                                  | 2.0     |         |         |         |         | –       |    |
| $\Delta\Phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} >$ | 0.4                                                                  |         |         |         |         |         |         |    |
| $\Delta\Phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\min} >$     | 0.4                                                                  |         |         |         |         |         | 0.2     |    |
| $E_T^{\text{miss}}/m_{\text{eff}}(N_j) >$                            | 0.3                                                                  | 0.25    |         |         | 0.2     |         | 0.3     |    |
| Aplanarity $>$                                                       | 0.04                                                                 |         |         |         |         |         | –       |    |
| $m_{\text{eff}}(\text{incl.}) \text{ [GeV]} >$                       | 1000                                                                 | 1400    | 1800    | 2200    | 2600    | 3000    | 1700    |    |

| Targeted signal                                                      | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \rightarrow qW\tilde{\chi}_1^0$ |         |         |         |         |         |         |  |
|----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|---------|---------|---------|---------|---------|---------|--|
| Requirement                                                          | Signal Region [Meff-]                                                                                                                    |         |         |         |         |         |         |  |
|                                                                      | 5j-1600                                                                                                                                  | 5j-2000 | 5j-2600 | 6j-1200 | 6j-1800 | 6j-2200 | 6j-2600 |  |
| $E_T^{\text{miss}} \text{ [GeV]} >$                                  | 250                                                                                                                                      |         |         |         |         |         |         |  |
| $p_T(j_1) \text{ [GeV]} >$                                           | 200                                                                                                                                      |         |         |         |         |         |         |  |
| $p_T(j_6) \text{ [GeV]} >$                                           | 50                                                                                                                                       |         |         |         | 100     |         |         |  |
| $ \eta(j_{1,\dots,6})  <$                                            | –                                                                                                                                        |         |         | 2.0     |         | –       |         |  |
| $\Delta\Phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} >$ | 0.4                                                                                                                                      |         | 0.8     |         | 0.4     |         |         |  |
| $\Delta\Phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\min} >$     | 0.2                                                                                                                                      | 0.4     |         |         | 0.2     |         |         |  |
| $E_T^{\text{miss}}/m_{\text{eff}}(N_j) >$                            | 0.15                                                                                                                                     | –       |         | 0.25    | 0.2     |         | 0.15    |  |
| $E_T^{\text{miss}}/\sqrt{H_T} \text{ [GeV}^{1/2}] >$                 | –                                                                                                                                        | 15      | 18      | –       |         |         |         |  |
| Aplanarity $>$                                                       | 0.08                                                                                                                                     | –       |         |         | 0.04    | 0.08    |         |  |
| $m_{\text{eff}}(\text{incl.}) \text{ [GeV]} >$                       | 1600                                                                                                                                     | 2000    | 2600    | 1200    | 1800    | 2200    | 2600    |  |

Table 10: Selection criteria and targeted signal models described in Section 7.1, used to define signal regions in the 0-lepton search, indicated by the prefix ‘Meff’ as the final discriminating variable used in the SRs. Each SR is labeled with the inclusive jet multiplicity considered (‘2j’, ‘3j’ etc.) together with the degree of background rejection. The latter is denoted by the value corresponding to the  $m_{\text{eff}}$  cut. The  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  cut in any  $N_j$ -jet channel uses a value of  $m_{\text{eff}}$  constructed from only the leading  $N_j$  jets ( $m_{\text{eff}}(N_j)$ ). However, the final  $m_{\text{eff}}(\text{incl.})$  selection, which is used to define the signal regions, includes all jets with  $p_T > 50$  GeV.

## 7.8 BOOSTED ANALYSIS

Exclusion limits for some of the signal models with longer decay chains containing W,Z or Higgs resonances can be improved by requiring a reconstructed resonance within a corresponding invariant mass window. From the models considered within this analysis this approach can be applied on the simplified model with gluino (squark) pair production followed by a one-step decay:

1.  $\tilde{g}(\tilde{q}) \rightarrow q\bar{q}'\tilde{\chi}_1^\pm(q\tilde{\chi}_1^\pm) \rightarrow q\bar{q}'W^\pm\tilde{\chi}_1^0(qW^\pm\tilde{\chi}_1^0),$
2.  $\tilde{g}(\tilde{q}) \rightarrow q\bar{q}\tilde{\chi}_2^0(q\tilde{\chi}_2^0) \rightarrow q\bar{q}Z\tilde{\chi}_1^0(qZ\tilde{\chi}_1^0)$

shown in Figure 50 and 51.

The two bosons decay according to their branching fractions (BR) and after applying the 0-lepton cuts mainly events with W's hadronically decaying ( $W \rightarrow q\bar{q}$ ) remain, whose BR is  $\sim 67\%$ . Depending on the mass parameter space ( $m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$ ), boson resonances may receive a high boost resulting in a small opening angle between their decay products. This occurs when mass difference between gluino (squark) and chargino (or  $\tilde{\chi}_2^0$ ) is small and the mass difference between chargino and neutralino large. In the x parameter term (Eq. (99)), in the gluino pair production case:

$$\frac{\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)}{\Delta m(\tilde{g}, \tilde{\chi}_1^0)} \sim 1 \quad (100)$$

and likewise for the squark case.

In such a situation, the resonances can be reconstructed as a single jet. The signal region definition for the boosted boson case takes advantage of the Jet Reclustering Tool [159] which provides large-R Jets, following the procedure described in Section 5.3. W(Z) boson candidates are identified by selecting the large-R jets lying in an invariant mass window centered on the boson masses.

7.8.1 Optimisation for Discovery with  $13.3 \text{ fb}^{-1}$  of pp Data

The first study of a signal region dedicated to boosted scenario, here named as **2jW**, has been made targeting an integrated luminosity of  $13.3 \text{ fb}^{-1}$ , corresponding to the dataset used in the previous run of the analysis in 2016 [211]. The signal region is optimized using gluino one-step grid. In the next section, the optimisation procedure is discussed.

*Optimisation Procedure*

An optimal set of cuts based on the discriminating variables described in Section 6.3, is chosen for **2jW** by optimising the value of the signal discovery significance at  $3\sigma$ , calculated from the expected number events of SUSY signal for a certain signal mass hypothesis and the SM backgrounds, with the uncertainty on the expected number of background events.

The optimisation was done studying the discovery reach in two masses scenario of  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (1400, 1350, 60), (1400, 1200, 60)$  GeV, at the integrated luminosity of  $13 \text{ fb}^{-1}$ .

Two complementary methods were used for significance calculation:

1. Significance computed with **BinominalExpP**<sup>4</sup> of the **RooStat** framework [212] to find the best discriminating variables and the range of cuts values. Since the systematic uncertainties depend on the number of background events, the size of the systematics uncertainties was estimated from a fit of the uncertainties from the 2015 analyses [188] with the following function (see Figure 54):

$$f(N) = \frac{a}{N^b} + c \quad (101)$$

where  $N$  is the number of SM background events in the signal region. Fitted parameter values are:

$$a = 0.40, \quad b = 0.53, \quad c = 0.077 \quad (102)$$

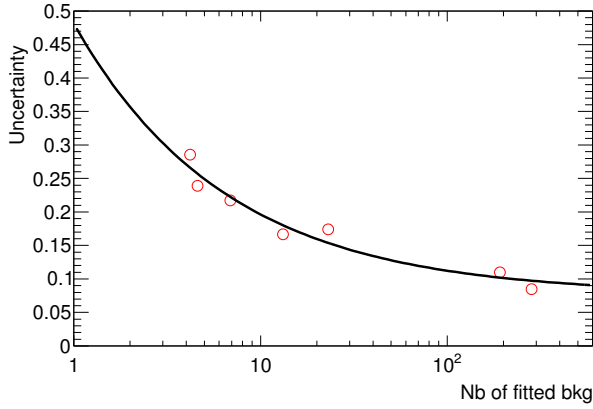


Figure 54: Systematic uncertainty of the 2015 analyses as a function of the predicted number of background events. Private communication from N.Makovec.

2. Significance computed with **HISTFITTER** including CRs and all uncertainties for the final event selection determination. The observed events in CRs are assumed to be the same as MC expectation. This method is the most accurate but much slower.

### *SR-2jW Optimisation Results*

The distribution of the variables chosen to have the best separation between signal and background are shown in Figure 55. Particularly,

<sup>4</sup> This function requires as inputs the observed number of events (equals to SUSY signal plus SM background), the expected SM background events, and the uncertainty on these SM background expectation. In addition, the optimisation using this significance formulae is equivalent to the optimisation using  $p_0$  values.

the distributions of the first and second most energetic large-R Jets masses ( $m(\text{Rj}_{1,2})$ ) show the peak inside the  $W$  boson mass range. The large-R Jets mass range is then chosen to be symmetrical around the  $W$  boson mass,  $[60, 100]$  GeV. The other variable distributions in Figure 55 are shown after the  $60 < |m(\text{Rj}_{1,2})| < 100$  GeV cuts are applied.

The optimal cut set is found by varying the other discriminant variables:  $\Delta\phi$ ,  $E_T^{\text{miss}}/\sqrt{H_T}$ ,  $m_{\text{eff}}(\text{incl.})$ . Various scans on the value of the cuts have been performed following the steps described above: 1. considering the significance, 2. studying the discovery reach on the GG-onestep signal hypothesis calculated with HISTFITTER. The set of the optimized cuts for **2jW** signal region is summarized in Table 11.

| Targeted signal                                                      | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ |
|----------------------------------------------------------------------|-----------------------------------------------------------------------|
| Requirement                                                          | Signal Region                                                         |
|                                                                      | <b>2jW</b>                                                            |
| $E_T^{\text{miss}} [\text{GeV}] >$                                   | 200                                                                   |
| $N_{j>0.4} \geq$                                                     | 2                                                                     |
| $p_T(\text{Rj}_1) [\text{GeV}] >$                                    | 200                                                                   |
| $p_T(\text{Rj}_2) [\text{GeV}] >$                                    | 200                                                                   |
| $m(\text{Rj}_1) [\text{GeV}]$                                        | [60,100]                                                              |
| $m(\text{Rj}_2) [\text{GeV}]$                                        | [60,100]                                                              |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} >$ | 0.6                                                                   |
| $E_T^{\text{miss}}/\sqrt{H_T} [\text{GeV}^{1/2}] >$                  | 20                                                                    |
| $m_{\text{eff}}(\text{incl.}) [\text{GeV}] >$                        | 2000                                                                  |

Table 11: Optimised signal region selection defined for gluino-pair production with one-step decay chain.

Figure 56 shows the expected discovery reach in the signal model targeting gluino-pair production with one-step decay of gluino, at the given integrated luminosity of  $13.3 \text{ fb}^{-1}$ . The contour of the discovery potential of the **2jW** is compared with the SR optimised for the analysis performed at  $13.3 \text{ fb}^{-1}$  [211]. As expected, the **2jW** improves the sensitivity of the analysis in the boosted scenario where  $\tilde{\chi}_1^\pm$  has nearly degenerate mass as the gluino, due to the dedicated selection on the large-R Jets mass, whereas such a portion of the parameter space is not covered by the other SRs using ordinary small-R jets.

### 7.8.2 Optimisation for Exclusion with $36.5 \text{ fb}^{-1}$ of pp Data

The signal region targeting boosted scenarios in SUSY simplified models with one-step decay to hadronically decaying bosons has been included in the main 0-lepton analysis selection. In order to expand the sensitivity and include also the case of gluino one-step decay via  $\tilde{\chi}_2^0$  to  $q\bar{q}Z\tilde{\chi}_1^0$  and the squark one-step decay via  $\tilde{\chi}_1^\pm$  to  $qW\tilde{\chi}_1^0$ , the boosted signal region

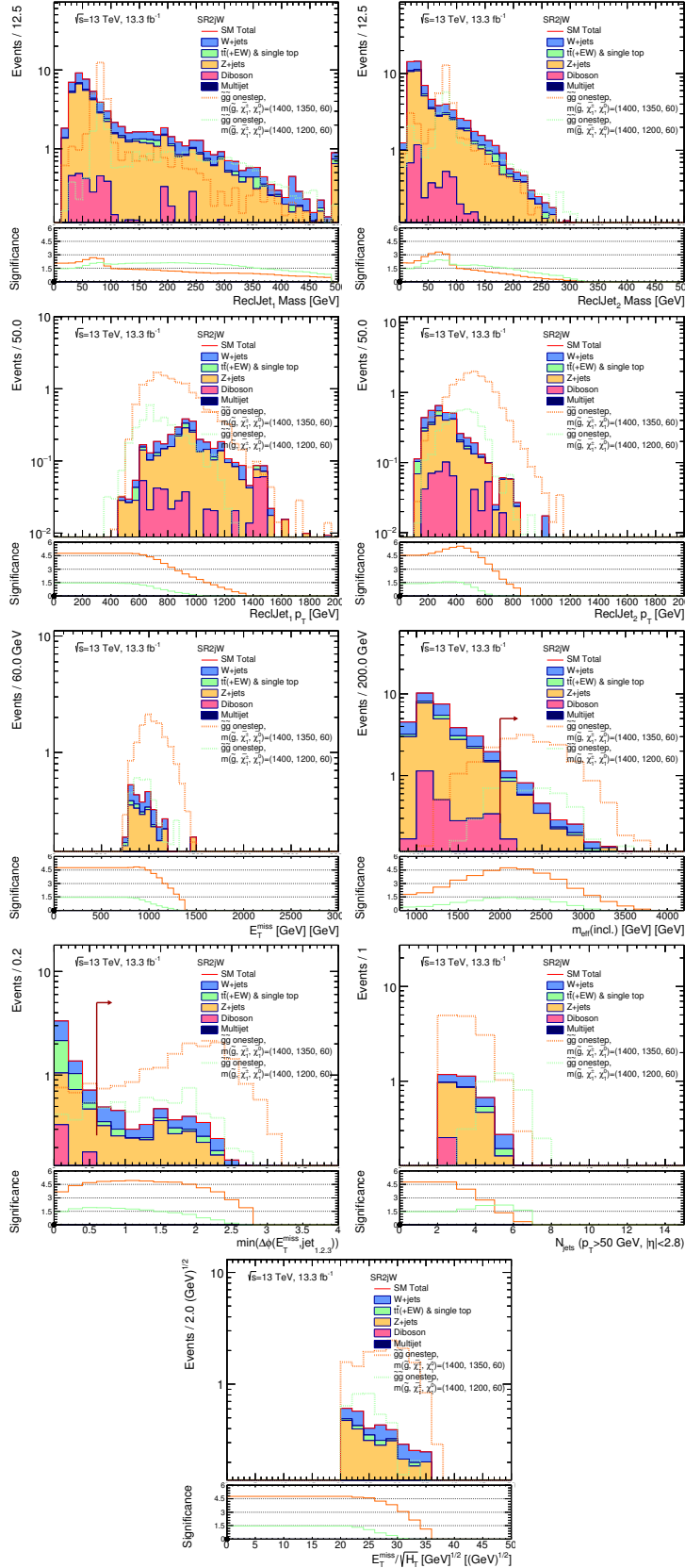


Figure 55: Marginal distributions for  $2jW$  for several signal samples and all background samples assuming a luminosity of  $13.3 \text{ fb}^{-1}$ . The arrow indicates the value of the cut on the corresponding variables. In the lower panel, the lines show the significance for an upper cut on the variable displayed. The last bin includes the overflow.

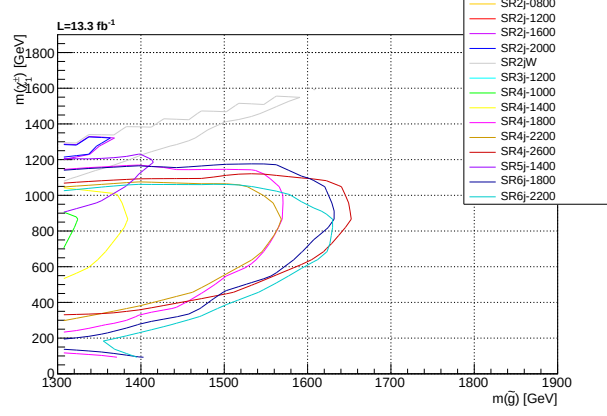


Figure 56: The expected  $3\sigma$  discovery reach for the gluino-pair production with one-step decay of gluino including W boson in the final state, for integrated luminosity  $13.3 \text{ fb}^{-1}$  and  $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}$ . These results are obtained using the `HistFitter` package based on `RooStats` [212].

has been splitted in two, distinguished by two different cut on the  $m_{\text{eff}}$  variable: **2jB-1600** and **2jB-2400**, where the "B" stands for bosons (W and Z).

In order to run the analysis with the full 2015+2016 dataset, all the SRs have been re-optimised at the integrated luminosity of  $36.5 \text{ fb}^{-1}$ . Since no statistically significant excess has been found in the previous iterations, the SR has been re-optimised to achieve the best exclusion power, i.e. the lowest expected CLs for any signal mass hypothesis.

The signal region **2jB-1600** has been optimized using the squark one-step grid  $(m_{\tilde{q}}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (1100, 1090, 60) \text{ GeV}$  point.

The signal region **2jB-2400** has been optimized using the gluino one-step grid  $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (1800, 1790, 60) \text{ GeV}$  point.

#### *SR-2jB's Optimisation Results*

Differently from the previous optimisation, the mass windows chosen  $[60, 110] \text{ GeV}$  are symmetrical with respect to the average of W, Z masses. The number of jets of the 2jBs regions has been left at  $\geq 2$  because the new **5j-2600** signal region has been added in order to cover the "intermediate boosted" region (where  $(m_{\tilde{g}/\tilde{q}} - m_{\tilde{\chi}_1^\pm}) \approx 200 \text{ GeV}$ ) in the exclusion fit. The **5j-2600** uses ordinary small-R jets, as stated in Table 10.

The discriminant variables chosen to have the best separation between signal and background for the two **2jB** regions are shown in Figure 57 - 60.

In Table 12, the final optimised selection cuts for the signal regions **2jB-1600** and **2jB-2400** are listed.

Top (bottom) plot in Figure 61 shows the expected exclusion reach in the signal model targeting gluino (squark)-pair production with one-



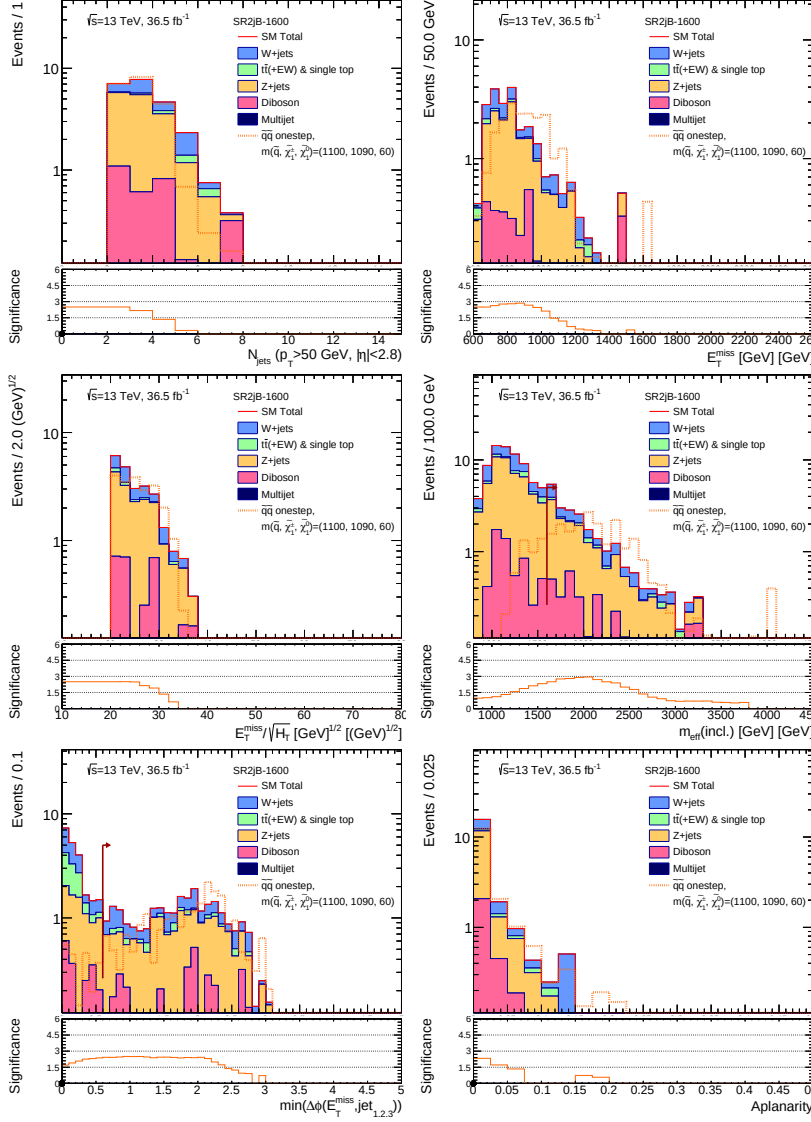


Figure 57: Marginal distributions for **2jB-1600** for a  $\tilde{q}\tilde{q}$  signal sample and all background samples assuming a luminosity of  $36.5 \text{ fb}^{-1}$ . The arrow indicates the value of the cut on the corresponding variables. In the lower panel, the line shows the significance for an upper (lower) cut on the variable displayed. The last bin includes the overflow.

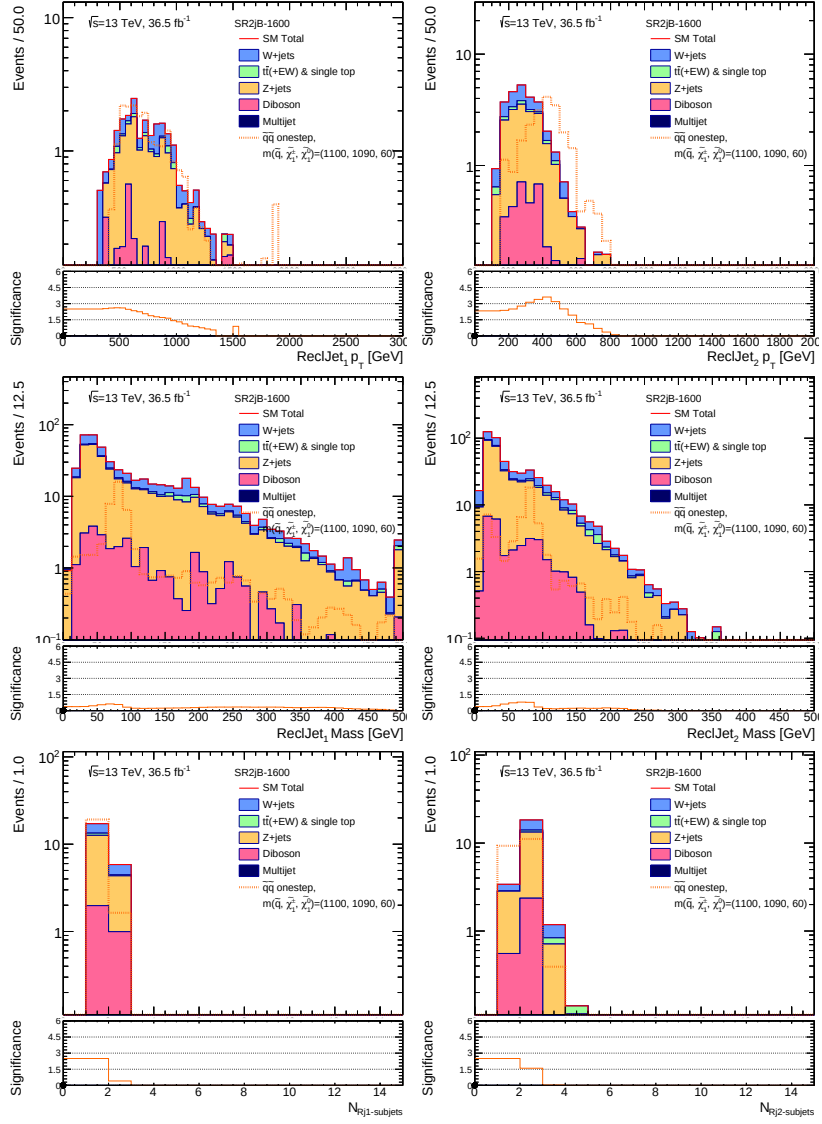


Figure 58: Marginal distributions for **2jB-1600** for a  $\tilde{q}\tilde{q}^*$  signal sample and all background samples assuming a luminosity of  $36.5 \text{ fb}^{-1}$ . The arrow indicates the value of the cut on the corresponding variables. In the lower panel, the line shows the significance for an upper (lower) cut on the variable displayed. The last bin includes the overflow.

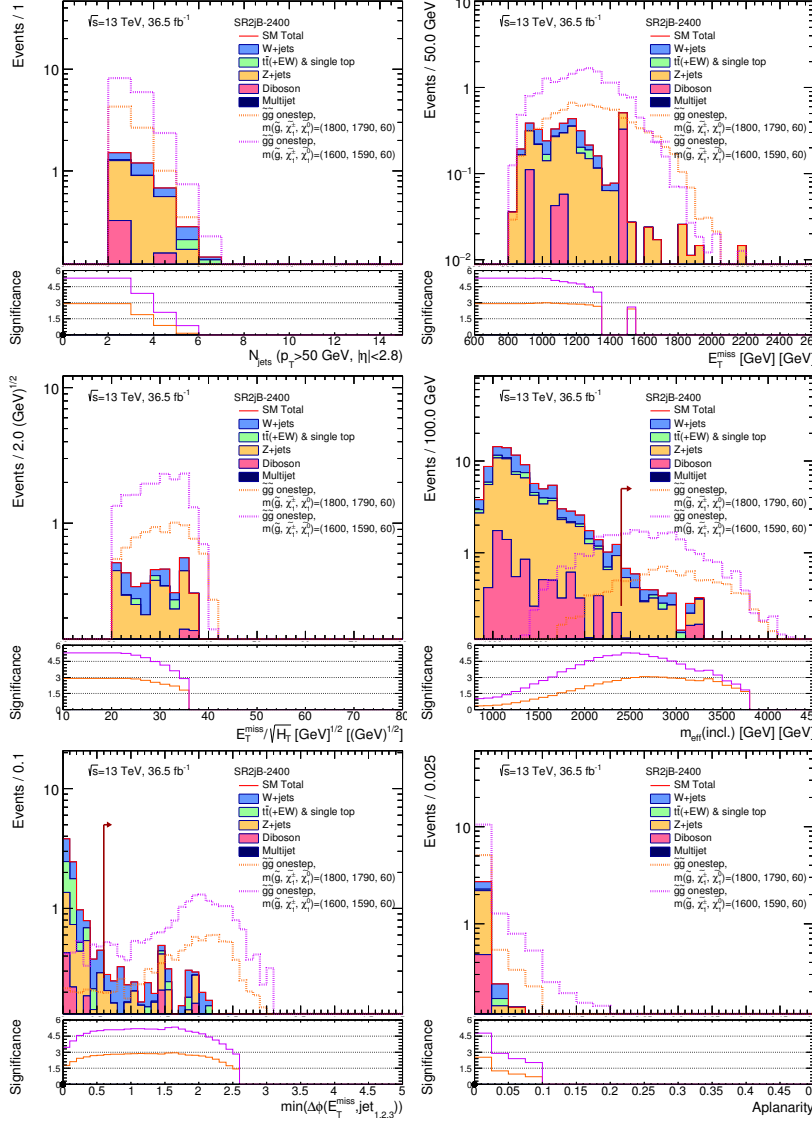


Figure 59: Marginal distributions for **2jB-2400** for two  $\tilde{g}\tilde{g}$  signal samples and all background samples assuming a luminosity of  $36.5 \text{ fb}^{-1}$ . The arrow indicates the value of the cut on the corresponding variables. In the lower panel, the line shows the significance for an upper (lower) cut on the variable displayed. The last bin includes the overflow.

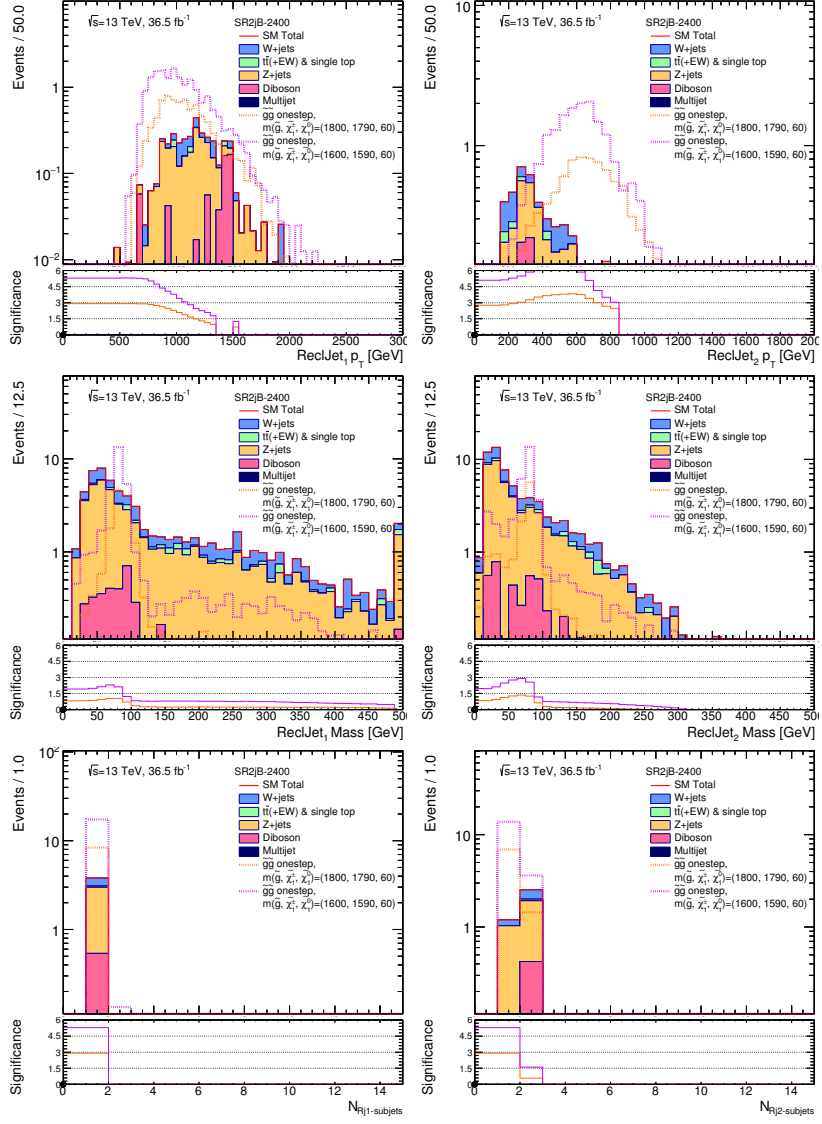


Figure 60: Marginal distributions for **2jB-2400** for two  $\tilde{g}\tilde{g}$  signal samples and all background samples assuming a luminosity of  $36.5 \text{ fb}^{-1}$ . The arrow indicates the value of the cut on the corresponding variables. In the lower panel, the line shows the significance for an upper (lower) cut on the variable displayed. The last bin includes the overflow.

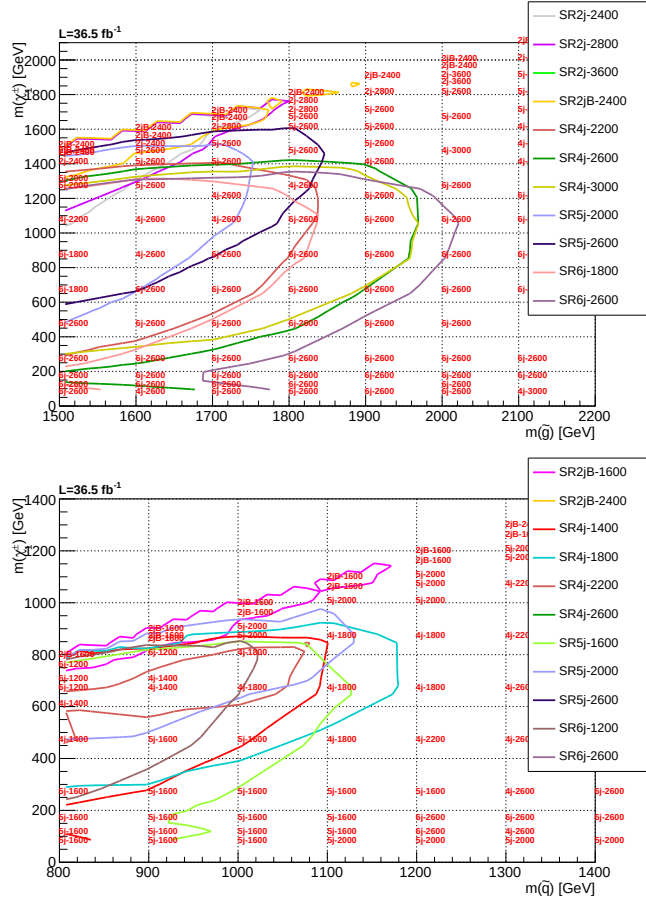


Figure 61: The expected 95% CL exclusion limits for the gluino- (top) and squark- (bottom) pair production with one-step decay chain resulting in  $W$  boson in the final state, for integrated luminosities of  $36.5 \text{ fb}^{-1}$  and  $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}$ . These results are obtained using the **HistFitter** package based on **RooStats** [212], also testing the performance of the combined fit in the corresponding signal and control regions CRW and CRT. Only signal regions giving the lowest expected CLs for one of the point are shown.

step decay of gluino (squark) via intermediate  $\tilde{\chi}_1^\pm$ , with fixed  $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}$  at the given integrated luminosity of  $36.5 \text{ fb}^{-1}$ . The effect of the **2jB** signal regions are visible in the compressed region of the parameter space, where they provide better sensitivity than the other SRs.

Figure 62 shows the exclusion limits for the gluino-pair production with one-step decay of gluino via intermediate  $\tilde{\chi}_2^0$  to  $Z$  boson in final state, at the given integrated luminosity of  $36.5 \text{ fb}^{-1}$ . Since the **2jB-2400** have been optimised for the  $\tilde{g}\tilde{g} \rightarrow q\bar{q}'W\tilde{\chi}_1^0$  case, the performance in the  $\tilde{g}\tilde{g} \rightarrow q\bar{q}Z\tilde{\chi}_1^0$  case do not show the same exclusion power.

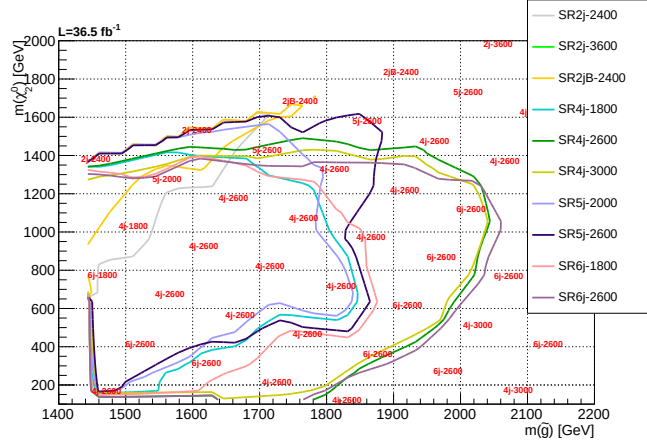


Figure 62: The expected 95% CL exclusion limits for the gluino-pair production with one-step decay with Z boson in the final state for integrated luminosities of  $36.5 \text{ fb}^{-1}$  and  $m_{\tilde{\chi}_1^0} = 1 \text{ GeV}$ . These results are obtained using the **HistFitter** package based on **RooStats** [212], also testing the performance of the combined fit in the corresponding signal and control regions CRW and CRT. Only signal regions giving the lowest expected CLs for one of the point are shown.

| Targeted signal                                                      | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ and $\tilde{q}\tilde{q}, \tilde{q} \rightarrow qW\tilde{\chi}_1^0$ |          |
|----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Requirement                                                          | Signal Region [Meff]                                                                                                                     |          |
|                                                                      | 2jB-1600                                                                                                                                 | 2jB-2400 |
| $E_T^{\text{miss}} [\text{GeV}] >$                                   | 250                                                                                                                                      |          |
| $p_T(\text{Rj}_1) [\text{GeV}] >$                                    | 200                                                                                                                                      |          |
| $p_T(\text{Rj}_2) [\text{GeV}] >$                                    | 200                                                                                                                                      |          |
| $m(\text{Rj}_1) [\text{GeV}]$                                        | [60,110]                                                                                                                                 |          |
| $m(\text{Rj}_2) [\text{GeV}]$                                        | [60,110]                                                                                                                                 |          |
| $\Delta\phi(\text{jet}_{1,2,(3)}, \vec{E}_T^{\text{miss}})_{\min} >$ | 0.6                                                                                                                                      |          |
| $\Delta\phi(\text{jet}_{i>3}, \vec{E}_T^{\text{miss}})_{\min} >$     | 0.4                                                                                                                                      |          |
| $E_T^{\text{miss}}/\sqrt{H_T} [\text{GeV}^{1/2}] >$                  | 20                                                                                                                                       |          |
| $m_{\text{eff}}(\text{incl.}) [\text{GeV}] >$                        | 1600                                                                                                                                     | 2400     |

Table 12: Optimised signal region selection defined for gluino(squark)-pair production with one-step decay.

## 7.9 BACKGROUND ESTIMATION

The estimation of the event yield of the Standard Model background processes in the signal regions defined above is either obtained with a semi-data driven technique using control regions, following the procedure described in Section 6.5, or estimated entirely using MC simulated data.

Four of the main background contribution are estimated in signal regions by designing four dedicated control regions:  $Z(\rightarrow \nu\nu)+\text{jets}$ ,  $W(\rightarrow l\nu)+\text{jets}$ , top and multijets backgrounds. The diboson background is instead estimated from MC sample normalised to the NLO cross-section predictions. The multijets background is estimated via a completely data-driven method.

### 7.9.1 Control Regions

The CR selection is designed to enhance the population of the dedicated background process it is dedicated to, while aiming to resemble as close as possible the selection used in the SRs, in order not to suffer from high systematic uncertainties coming from the extrapolation to the SR. Therefore, the  $\text{jet-}p_T$  and the  $m_{\text{eff}}$  thresholds are the same as used in the SRs. Each of the SR has its dedicated set of four CRs. The control region definitions are given in Table 14.

To test the robustness of the background estimate procedure, validation regions are built with a selection even closer to the SR but in a way that the signal is not expected to be present, as described in Section 6.5.1. This check is done before the signal regions are unblinded, i.e. before looking at the actual data selected in the signal regions.

#### *Control Region for $Z+\text{jets}$*

The background contribution coming from the  $Z+\text{jets}$  process is irreducible since the selection in the SRs does not distinguish those events from supersymmetrical ones. The control region dedicated to  $Z+\text{jets}$  estimation uses a different but kinematically similar process,  $\gamma+\text{jets}$  events. Specifically, it has been found that for  $p_T(\gamma) \gg m_Z$ , say 150 GeV, the kinematics of those events closely resemble  $Z(\rightarrow \nu\nu)+\text{jets}$  [213]. To provide an estimate of the  $p_T(Z)$ , the reconstructed photon  $p_T(\gamma)$  is added to the  $E_T^{\text{miss}}$ , so that  $(E_T^{\text{miss}})' = E_T^{\text{miss}} + p_T(\gamma)$  is used in the event. The CR is therefore named CRY after the  $\gamma$  (Y) process.

When using CRY to constrain the  $Z+\text{jets}$  background, the cross section ratio between  $\gamma+\text{jets}$  and  $Z+\text{jets}$  have to be taken into account. Generator predictions for  $\gamma+\text{jets}$ , using LO cross section, can vary significantly in rate causing a significant increase in the systematic uncertainties for the prediction of  $Z+\text{jets}$ . This uncertainty is dominant at low  $p_T$ , so that a correction factor to the  $\gamma+\text{jets}$  MC prediction in CRY can be derived using a looser CR selecting  $Z(\rightarrow ll)+\text{jets}$  ( $l = e, \mu$ ) events with invariant mass lying in a range of 25 GeV around the mass of

|               |                   |
|---------------|-------------------|
| nJet $\geq 2$ | 1.560 $\pm$ 0.035 |
| nJet $\geq 3$ | 1.641 $\pm$ 0.045 |
| nJet $\geq 4$ | 1.668 $\pm$ 0.068 |
| nJet $\geq 5$ | 1.680 $\pm$ 0.116 |
| nJet $\geq 6$ | 2.257 $\pm$ 0.261 |

Table 13: Values of  $\kappa$  factor, the uncertainties are the statistical uncertainties due to the limited statistics in the control regions.

the  $Z$  boson, and satisfying  $E_T^{\text{miss}} > 250$  GeV,  $E_T^{\text{miss}}/\sqrt{H_T} > 14$  GeV $^{1/2}$  and  $m_{\text{eff}}(\text{incl.}) > 1200$  GeV, where the two leptons are treated as contributing to  $E_T^{\text{miss}}$ . Such an auxiliary control region with enough events available is named CRZL, while the analogous auxiliary CR with looser selection on  $m_{\text{eff}}$  and  $E_T^{\text{miss}}/\sqrt{H_T}$  using  $\gamma$ +jets events is named CRYL. The correction factor  $k$  is then obtained with a data-driven calculation that reads:

$$\begin{aligned}
\kappa &= \left( \frac{N_{\text{CRYL}}^{\gamma+\text{jets,data}}}{N_{\text{CRZL}}^{Z\ell\ell,\text{data}}} \right) / \left( \frac{N_{\text{CRYL}}^{\gamma+\text{jets,MC}}}{N_{\text{CRZL}}^{Z\ell\ell,\text{MC}}} \right) \\
&= \frac{N_{\text{CRYL}}^{\gamma+\text{jets,data}} \cdot N_{\text{CRZL}}^{Z\ell\ell,\text{MC}}}{N_{\text{CRYL}}^{\gamma+\text{jets,MC}} \cdot N_{\text{CRZL}}^{Z\ell\ell,\text{data}}} \\
&= \frac{(N_{\text{CRYL}}^{\text{data}} - N_{\text{CRYL}}^{\text{bkg}}) \cdot N_{\text{CRZL}}^{Z\ell\ell,\text{MC}}}{N_{\text{CRYL}}^{\gamma+\text{jets,MC}} \cdot (N_{\text{CRZL}}^{\text{data}} - N_{\text{CRZL}}^{\text{bkg}})}
\end{aligned} \tag{103}$$

where *data* refers to measured number of events while MC to simulated number of events. The kappa factors are computed for various jet multiplicity, yielding values from 1.56 to 2.26 for two to six jets, as shown in Table 13. This gives overall factors greater than 1 mainly attributed to data/MC discrepancy observed in CRY attributed to use of LO MC without NLO k-factor corrections. Therefore,  $\kappa$  measures the difference between data and MC of  $\gamma$ +jets/ $Z$ +jets and in particular it cancels the dependence on total cross section calculation for the two processes. Being  $\kappa$  a ratio, many systematics uncertainties drop out in its calculation.

This factor is then used to correct the transfer factor  $\text{TF}(\gamma \rightarrow Z(\rightarrow \nu\nu))$ :

$$N_{\text{SR}}^{Z\nu\nu,\text{pred}} = N_{\text{SR}}^{Z\nu\nu,\text{MC}} \cdot \frac{N_{\text{CRY}}^{\gamma+\text{jets,data}}}{N_{\text{CRY}}^{\gamma+\text{jets,MC}} \cdot \kappa} \tag{104}$$

The systematic uncertainty on the total expected background due to the usage of the  $k$  factor varies in a range of 1-2%.

#### Control Region for $W$ +jets and Top

The control regions dedicated to the estimation of the background yield coming from  $W$ +jets and Top events are named CRW and CRT, respectively. They select events with  $W(\rightarrow l\nu)$ +jets and semileptonic



$t\bar{t}$  ( $t\bar{t} \rightarrow b\bar{b}q q' l \nu$ ) by requiring the presence of a high-purity lepton with  $p_T(l) > 27$  GeV,  $E_T^{\text{miss}}$ , and by requiring the transverse mass of the lepton- $E_T^{\text{miss}}$  system to be consistent with a leptonic W decay, i.e.  $30 < m_T(l, E_T^{\text{miss}}) < 100$  GeV. The two CRs are distinguished by the requirement of a b-tag jet in the CRT while CRW selects only events with zero b-tag jets.

The selected lepton is added to the list of selected jets in the events and used to recalculate jet-dependent quantities. This is motivated by the fact that for both background the most number of events in the signal region contain leptons that have faked jets (through misidentification or the lepton being a  $\tau$ ).

In order to increase the number of CR data events without significantly increasing the theoretical uncertainties brought by the transfer factor into the SRs, the requirements on  $|\eta_{\text{jet}}|$ ,  $\Delta\phi$ , and aplanarity are omitted in CRW(T). In addition to that, for the CRW(T) corresponding to the SRs requiring  $m_{\text{eff}} > 2200$  GeV, the further requirements on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  are omitted too. For CRT only, the  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  requirements are skipped also in case the corresponding SRs have 2j multiplicity.

#### *Control Region for QCD Multijets*

The contribution of the QCD Multijets event yield in the background is estimated through a data-driven technique, described in Section 7.9.4. In order to enhance the number of QCD events in the CRQ population, the signal region cuts dedicated to the QCD suppression are modified. The angular selection on  $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})$  is reversed and tightened (from  $\Delta\phi > 0.4$  to  $< 0.2$ ), so that only events where the  $E_T^{\text{miss}}$  is very much aligned in the jet direction are selected. This is indeed a typical topology for events with mismeasured jets or with neutrinos coming from heavy flavour decays. To improve the purity of the sample and better reject events from W or  $t\bar{t}$  decays with  $\tau$  leptons at low  $\Delta\phi$ , also the selection cuts on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$  (when appropriate) are reverted.

#### *7.9.2 Validation Regions*

The robustness of the background estimate obtained using the control regions is tested in a further set of regions, called validation regions (VR) and described in Section 6.5.1. Each SR is provided with a set of VRs for each of the background processes, in order to test the kinematical and topological extrapolation from the CRs to each of the SRs. The fit result in the control regions is extrapolated to the validation regions with the same procedure as to the signal region, so one can obtain the background prediction in regions with no signal contamination.

For each of the control regions, a validation region is typically named after a selection cut which is reintroduced as defined in the SR after being reverted or omitted in the control region.

| CR  | SR background                             | CR process                                   | CR selection                                                                                                                               |
|-----|-------------------------------------------|----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| CRY | $Z(\rightarrow \nu\bar{\nu})+\text{jets}$ | $\gamma+\text{jets}$                         | Isolated photon                                                                                                                            |
| CRQ | Multi-jet                                 | Multi-jet                                    | SR with reversed requirements on<br>(i) $\Delta\phi$ and (ii) $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$<br>or $E_T^{\text{miss}}/\sqrt{H_T}$ |
| CRW | $W(\rightarrow \ell\nu)+\text{jets}$      | $W(\rightarrow \ell\nu)+\text{jets}$         | $30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$ , b-veto                                                                 |
| CRT | $t\bar{t}(\text{+EW})$ and single top     | $t\bar{t} \rightarrow b\bar{b}q q' \ell \nu$ | $30 \text{ GeV} < m_T(\ell, E_T^{\text{miss}}) < 100 \text{ GeV}$ , b-tag                                                                  |

Table 14: Summary of CRs used in the 0-lepton analysis. The main SR backgrounds in each case, the process used to model the background, and the main CR requirement(s) are listed. The  $p_T$  of high-purity leptons ( $\gamma$ ) used to select CR events must exceed 27 (150) GeV. The jet- $p_T$  thresholds and  $m_{\text{eff}}(\text{incl.})$  selections match those used in the corresponding SRs.

#### VRs for Z Background

- VRZ selects  $Z(\rightarrow \ell\ell)+\text{jets}$  ( $\ell = e, \mu$ ) events and then applies a somewhat looser selection than that used in the SR to pseudo-events in which the reconstructed  $Z$  boson  $p_T$  has been added to the  $E_T^{\text{miss}}$  vector ( $E_T^{\text{miss}'} = |E_T^{\text{miss}} + p_T^Z|$ ) to provide an estimate of the  $p_T$  of  $Z$  bosons decaying to neutrinos in the SR. A looser selection with respect to that used for the SR is necessary because otherwise this VR would suffer from a lack of statistics, owing to the factor 3 smaller branching ratio for  $Z(\rightarrow \ell\ell)$  ( $\ell = e, \mu$ ) compared with  $Z(\rightarrow \nu\nu)$ . So cuts on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  (or  $E_T^{\text{miss}}/\sqrt{H_T}$ ),  $\Delta\phi$ , jet  $\eta$  and aplanarity are not applied.
- VRZf is similar to VRZ with additional cuts on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$ ,  $\Delta\phi$ , jet  $\eta$  and aplanarity as used in the corresponding SR.

#### VRs for W Background

- VRWf: As for CRW with additional cuts on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$ ,  $\Delta\phi$ , aplanarity and  $|\eta(j_{1,2,,})|$  as used in the corresponding SR.
- VRWdPhi: As for CRW with additional cut on  $\Delta\phi$  as used in the corresponding SR.
- VRWm: As for CRW with additional cut on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$  as used in the corresponding SR.
- VRWAp: As for CRW with additional cut on aplanarity as used in the corresponding SR.
- VRWeta: As for CRW with additional cut on  $|\eta(j_{1,2,,})|$  as used in the corresponding SR.

- VRWMf: As for VRWf but lepton is treated as a missing particle instead of being considered as a jet.

#### *VR for Top Background*

- VRTf: As for CRT with additional cuts on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$ ,  $\Delta\phi$ , aplanarity and  $|\eta(j_{1,2,,})|$  as used in the corresponding SR.
- VRTdPhi: As for CRT with additional cut on  $\Delta\phi$  as used in the corresponding SR.
- VRTm: As for CRT with additional cut on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$  as used in the corresponding SR.
- VRTAp: As for CRT with additional cut on aplanarity as used in the corresponding SR.
- VRTeta: As for CRT with additional cut on  $|\eta(j_{1,2,,})|$  as used in the corresponding SR.
- VRTMf: As for VRTf but lepton is treated as a missing particle instead of being considered as a jet.

#### *VRs for Multijet Background*

The following regions are not to test only multijet background but all background in 0-lepton channel.

- VRQ1: As for CRQ except that the cut on  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  or  $E_T^{\text{miss}}/\sqrt{H_T}$  is as for SR. Enhanced in QCD jet production with respect to the signal region. Sensitive to QCD jet extrapolation along  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$ .
- VRQ2: As for CRQ except that the cut on  $\Delta\phi$  is as for SR. Sensitive to QCD jet extrapolation along  $\Delta\phi$ .
- VRQ3: As for VRQ1 but with  $0.2 < \Delta\phi < 0.4, i = \{1, 2, (3)\}$  [or  $0.1 < \Delta\phi < 0.2, p_T > 50$  GeV only for SR 4j,5j,6j] so that multijet contribution is smaller than VRQ1 and is suited for validation of non-multijet background.
- VRQ4: As for VRQ2 but  $0.2 < \Delta\phi < 0.4, i = \{1, 2, (3)\}$  [or  $0.1 < \Delta\phi < 0.2, p_T > 50$  only for SR 4j,5j,6j] so that multijet contribution is larger than VRQ2 and is suited for validation of multijet background.

Validation regions for the multijets background are schematically summarized on Figure 63.

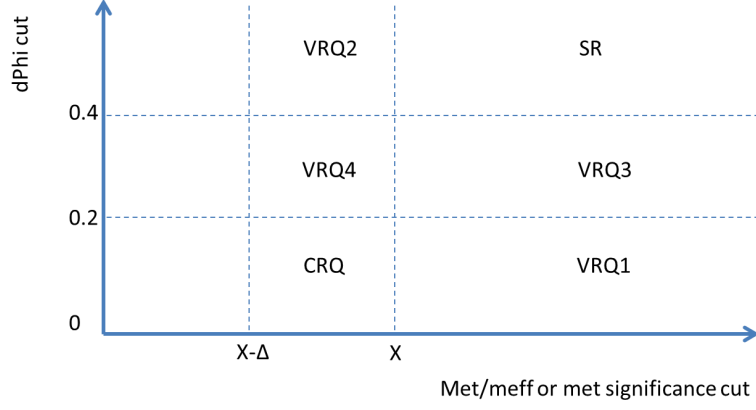


Figure 63: Validation regions for multijets background where  $X$  is the signal region cut value and  $X$  varies from 14 to 26 for  $E_T^{\text{miss}}$  significance ( $E_T^{\text{miss}}/\sqrt{H_T}$ ) and from 0.15 to 0.3 for  $E_T^{\text{miss}}/m_{\text{eff}}(N_j)$  depending on the signal region.

### 7.9.3 Fake Lepton Background

Fake-lepton backgrounds are ignored in control regions using selection on leptons (CRW, CRT and VRZ). In CRW and CRT, fake-lepton background has been found to considerably decrease with the increase of  $E_T^{\text{miss}}$  by checking it with a data-driven event estimation using early data. In VRZ region, the leptons are required to be of the *tight* type, which reduce this background even further.

### 7.9.4 QCD Multijet Background Estimation

The baseline multijet background estimation method is a fully data-driven approach called the *jet smearing* method [213]. The method works in event topologies where jet mismeasurements and neutrinos in jets from heavy flavour decays lead to fake- $E_T^{\text{miss}}$ .

To obtain a data-driven estimate of the multijet background, events containing jets, but low- $E_T^{\text{miss}}$  are used as *seeds*. The jet four-vectors of the seeds are smeared using a resolution function called *jet response function*, which quantifies the fluctuation in jet- $p_T$ . The jet- $p_T$  response function  $R$  is defined as:

$$R = \frac{p_T^{\text{reco}}}{p_T^{\text{truth}}}, \quad (105)$$

where  $p_T^{\text{reco}}$  is the reconstructed  $p_T$  of the jet and  $p_T^{\text{truth}}$  is the truth- $p_T$  of the jet, using the truth information (i.e. the information from the event generation, before the detector reconstruction and simulation).

The methods works in several steps:

1. The jet response function is firstly obtained from MC simulation by matching the truth- $p_T$  of the jets with the reconstructed  $p_T$  using a cone of  $\Delta R < 0.3$ . The  $p_T$  of the truth jet takes into account the energy of electrons, muons, and neutrinos. The jets in the events must be separated by  $\Delta R > 0.6$ ;

2. A dataset of low- $E_T^{\text{miss}}$  events, named *seeds*, is selected in data;
3. The response function  $R$  from point 1 is iteratively modified by smearing the seed events from point 2: the function width is parametrised and the tail modified, until agreement between the obtained pseudo-data and data in a special control region sensitive to the jet response is obtained;

The selected smeared events using the data-constrained function are used to obtain estimated distributions in the control and signal regions. The smeared missing transverse momentum  $\vec{E}_T^{\text{miss}'}$  is given by:

$$(\vec{E}_T^{\text{miss}})' = (\vec{E}_T^{\text{miss}})^{\text{seed}} - \sum_i \vec{p}_T'(j_i) + \sum_i \vec{p}_T(j_i) \quad (106)$$

where the primes are used to denote the smeared quantities. The  $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$  distributions can be then similarly obtained from smearing and be used to calculate the transfer factors from the events with low- $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$  selected in CRQ to the higher- $\Delta\phi(\text{jet}, \vec{E}_T^{\text{miss}})_{\text{min}}$  events in the SRs.

The method makes some assumptions. First, that all sources of jet fluctuations can be included in just one  $R$ . Then, that the response function does not depend on other properties. Validation regions dedicated to the QCD estimation are built in order to test the robustness of the method.

#### 7.9.5 Pre-fit Control Region Distributions

The comparison between data and Monte Carlo simulated samples before the simultaneous fit is shown in Figure 64-67 in the distribution of the  $m_{\text{eff}}$  variable for each of the CRs for a representative choice of SRs: **2j-1200**, **4j-2200**, **5j-1700**, **6j-1800**. Given the statistical and systematic uncertainties, the overall data versus Monte Carlo agreement for the baseline SM prediction is satisfying. Nonetheless, the following features are observed:

- Monte Carlo simulation for  $W+\text{jets}$ ,  $\gamma+\text{jets}$ , tends to overestimate the data at high jet multiplicity.
- Monte Carlo simulation for Top tends to overestimate the data in the high- $m_{\text{eff}}$  region.

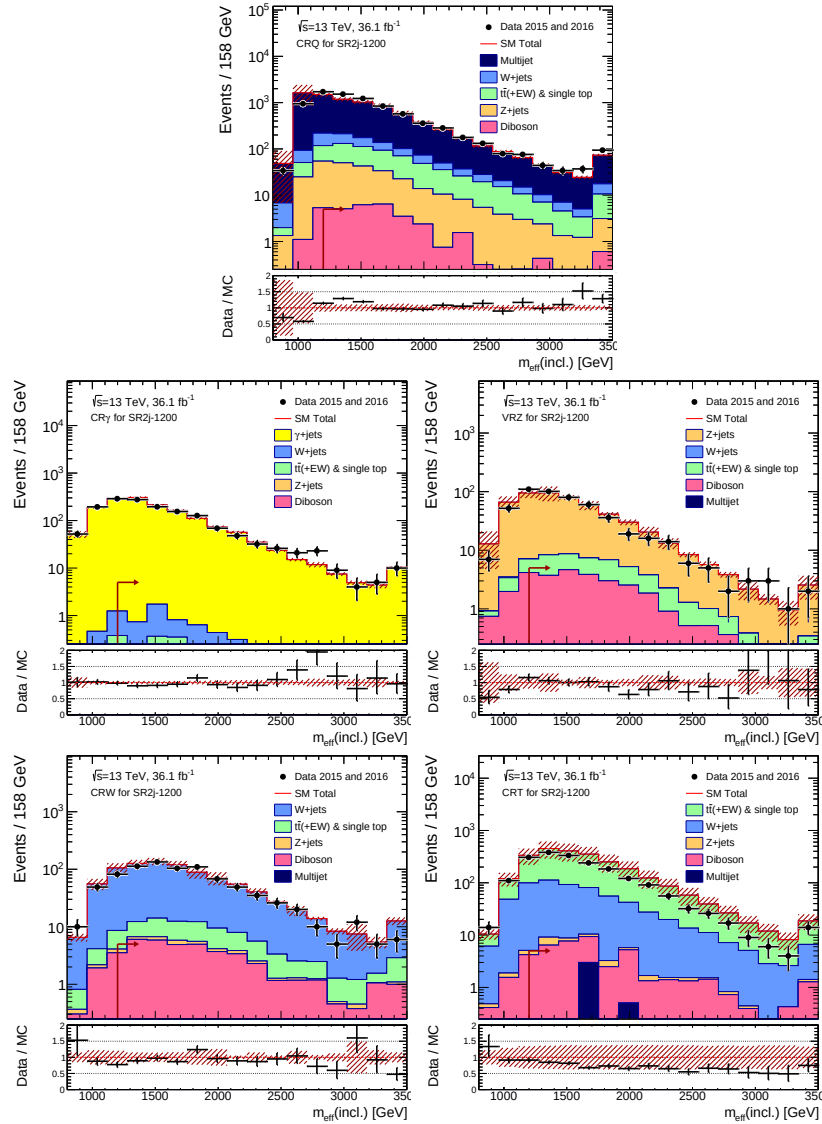


Figure 64: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **2j-1200** control regions CRQ (Upper), CRY (Middle left), VRZ (Middle right), CRW (Lower left) and CRT (Lower right) with a loose  $m_{\text{eff}}$  final cut. The histograms denote the MC background expectations, normalised to data luminosity. Cross section are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1 and Multijet in CRQ, Z+jets in VRZ, W+jets in CRW and top in CRT are normalised to data. The hatched error bands denote the combined experimental, MC statistical uncertainties.

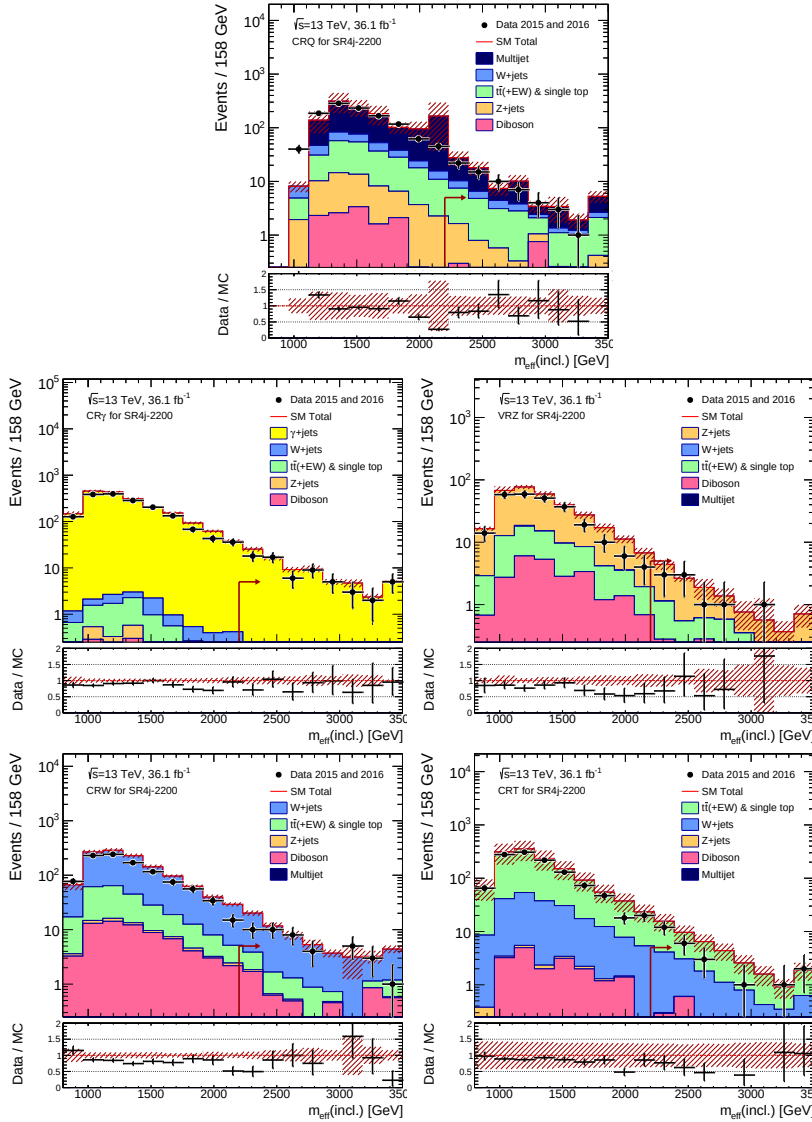


Figure 65: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **4j-2200** control regions CRQ (Upper), CRY (Middle left), VRZ (Middle right), CRW (Lower left) and CRT (Lower right) with a loose  $m_{\text{eff}}$  final cut. The histograms denote the MC background expectations, normalised to data luminosity. Cross section are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1 and Multijet in CRQ, Z+jets in VRZ, W+jets in CRW and top in CRT are normalised to data. The hatched error bands denote the combined experimental, MC statistical uncertainties.

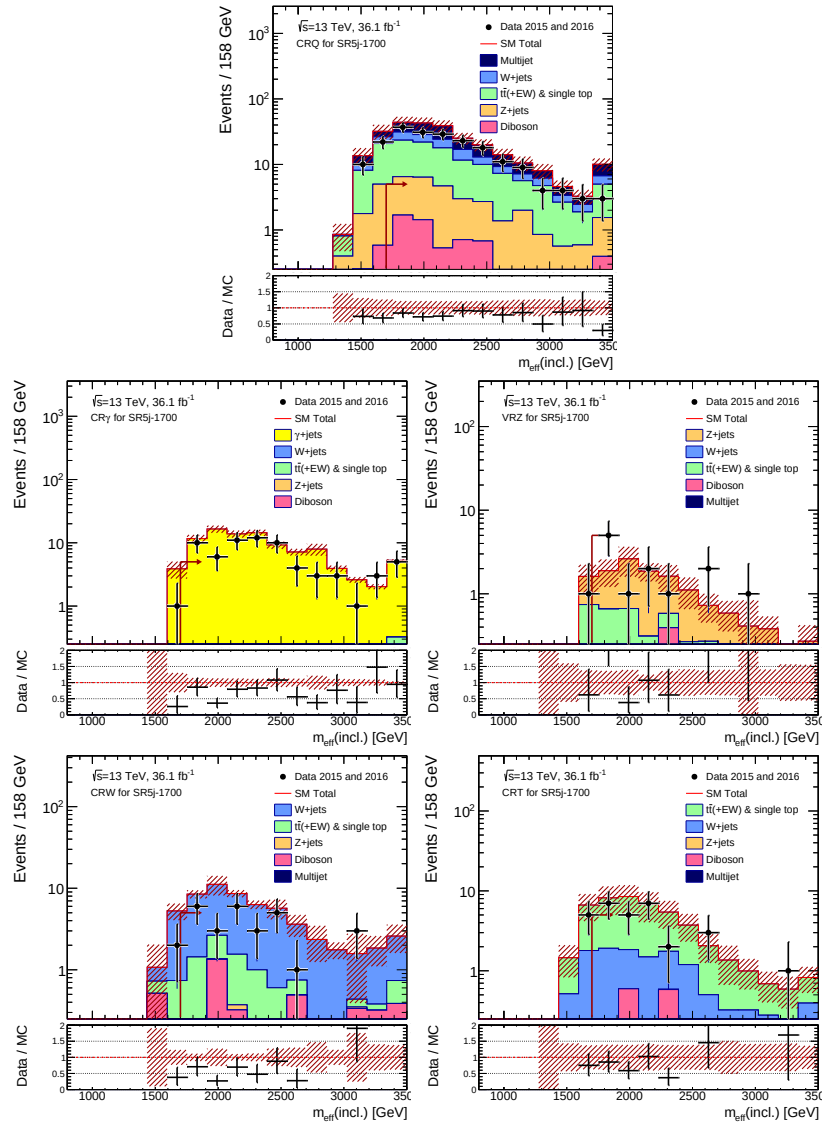


Figure 66: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **5j-1700** control regions CRQ (Upper), CRY (Middle left), VRZ (Middle right), CRW (Lower left) and CRT (Lower right) with a loose  $m_{\text{eff}}$  final cut. The histograms denote the MC background expectations, normalised to data luminosity. Cross section are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1 and Multijet in CRQ, Z+jets in VRZ, W+jets in CRW and top in CRT are normalised to data. The hatched error bands denote the combined experimental, MC statistical uncertainties.



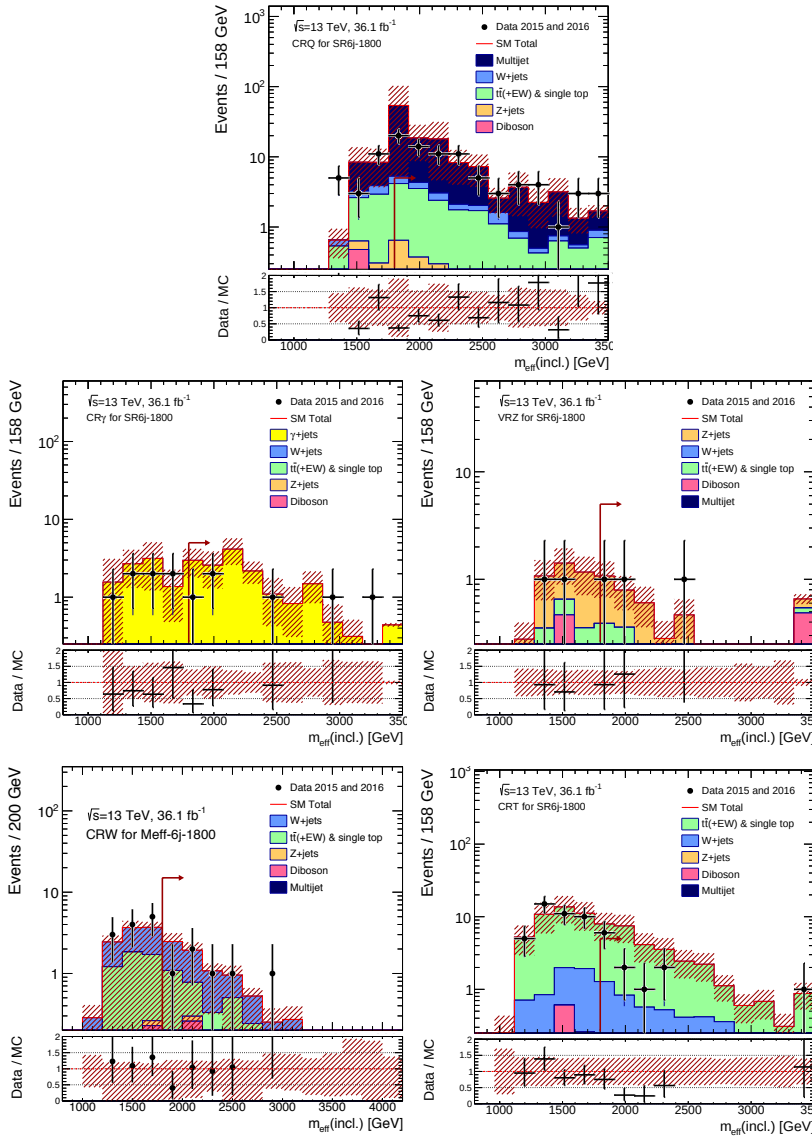


Figure 67: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **6j-1800** control regions CRQ (Upper), CRY (Middle left), VRZ (Middle right), CRW (Lower left) and CRT (Lower right) with a loose  $m_{\text{eff}}$  final cut. The histograms denote the MC background expectations, normalised to data luminosity. Cross section are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1 and Multijet in CRQ, Z+jets in VRZ, W+jets in CRW and top in CRT are normalised to data. The hatched error bands denote the combined experimental, MC statistical uncertainties.

### 7.9.6 Control Region Selection for Boosted Analysis

As for the others SRs, the same set of Control Regions are defined for signal regions **2jB-1600** and **2jB-2400** (hereafter referred as **SR-2jBs**). Since selection of SR-2jBs differs from the other SRs by the cuts on reclustered large-R jets instead of usual jets, the CR selection for SR-2jBs also relies on the cuts on large-R jets. All CRs associated with SR-2jBs have a cut on low large-R jet mass (20 GeV) for the first two leading large-R jets. In order to keep the CRs close to the SR-2jBs definition, a cut on only the first large-R jet mass window is applied. The CRs additional selection for **2jBs** is shown in Table 15.

The  $m_{\text{eff}}$  variable distributions in each of the CRs associated with the boosted signal regions **2jBs** are shown in Figure 68 and 69. A relatively good agreement between the MC prediction and data is found in the CRs.

| Cut                                                                                        | Control Region |     |     |     |
|--------------------------------------------------------------------------------------------|----------------|-----|-----|-----|
|                                                                                            | CRY            | CRW | CRT | CRQ |
| $p_T(Rj_{1,2})$                                                                            | As for SR cuts |     |     |     |
| $m(Rj_{1,2})$                                                                              | > 20 GeV       |     |     |     |
| $m(Rj_1)$                                                                                  | [60,110] GeV   |     |     |     |
| $m_{\text{eff}}(\text{incl.}), \Delta\phi, E_T^{\text{miss}}/m_{\text{eff}}(\text{incl.})$ | As for SR cuts |     |     |     |

Table 15: 2jBs Control Regions additional selections.

#### Reclustered-Jet mass Cut Validation Regions

Validation Regions **VRWB**, **VRTB**, **VRQB**, **VRYB** have the same cut on  $m(Rj_{1,2})$  in [60, 110] GeV range applied as in the SR-2jBs, in order to validate the removed cut with respect to CRW, CRT, CRQ, CRY.

#### Background Estimation for Boosted Analysis

Standard Model background estimation for Boosted Signal Regions **2jB-1600** and **2jB-2400** is performed with the same techniques as for the other SRs. The specific control region selection cuts for the SRs are reported in Table 15. The distributions of the main discriminant variables (without the cut on it, whose value is shown by an arrow) corresponding to Signal Regions **2jB-1600** and **2jB-2400** using the full Run2 dataset ( $36.1 \text{ fb}^{-1}$ ) can be found in Appendix A, in Figures 86-96. A general agreement between data and MC is observed.

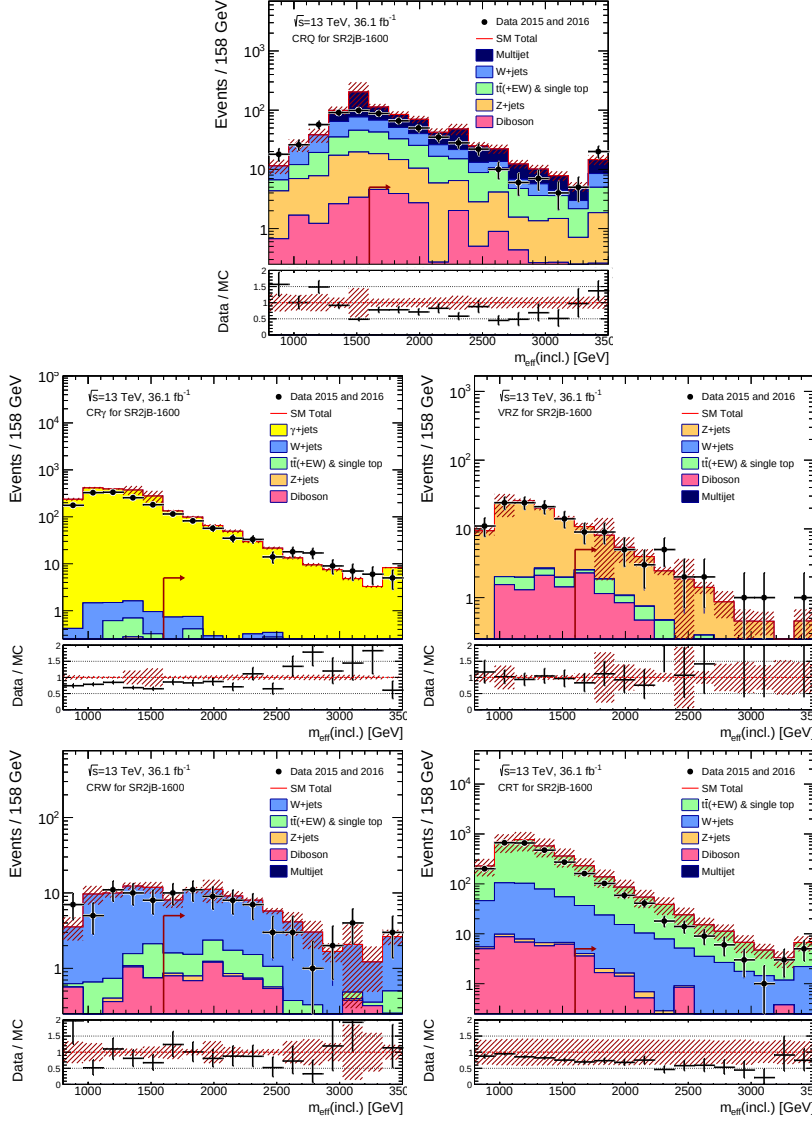


Figure 68: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **2jB-1600** control regions CR $\gamma$  (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

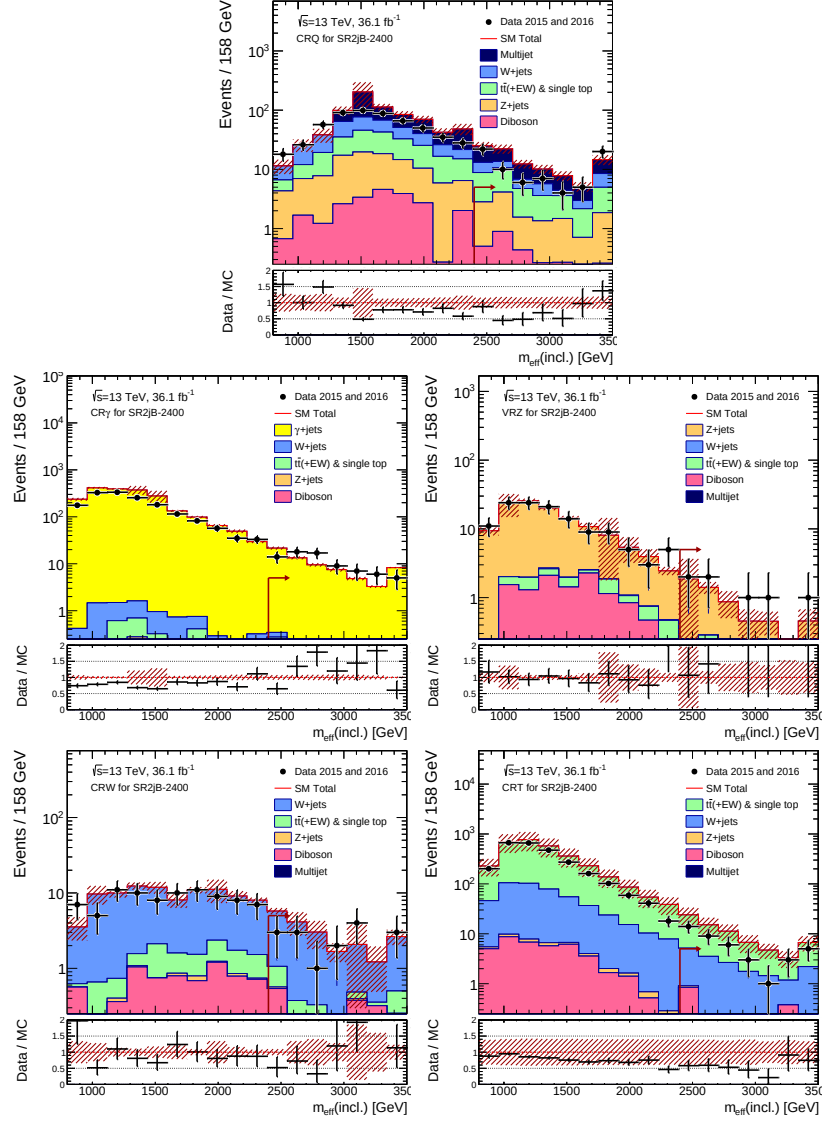


Figure 69: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

## 7.10 SYSTEMATIC UNCERTAINTIES

Several different sources of systematic uncertainties, both for the background and the signal, need to be identified and studied before including them in the likelihood-fit. Systematic uncertainties coming from the reconstruction of physical objects as well as uncertainties related to the modeling of simulation of the physics processes can affect the expected yield in the control regions, validation and signal regions, resulting in uncertainty of the excluded SUSY parameter-space, which is the ultimate goal of the analysis.

### 7.10.1 *Uncertainties on Background*

The systematic uncertainties on the Standard Model background prediction come from many different sources. They affect the final results and impact on the transfer factors from the CRs to the SRs. Three types of systematic uncertainties can be distinguished:

- Experimental** uncertainties related to the understanding of the detector and its performances in the detection of the particles. They include, e.g. the jet energy scale (JES) and resolution (JER), that affect the distribution of the  $p_T$  of the jets and subsequently the  $E_T^{\text{miss}}$  calculation, and other uncertainties on the  $b$ -tag,  $E_T^{\text{miss}}$ , lepton and photon reconstruction.
- Theoretical** uncertainties related to the physics modeling in the event simulations. They include the choice of the generator used, the PDF, the factorisation and renormalisation scales influencing the simulated events.
- Extrapolation** uncertainties related to the extrapolation procedure from the CRs to the VRs and finally to the SRs.

The primary sources of systematic uncertainties for background simulated processes estimated via transfer factors are the theoretical uncertainties on process modeling, JES and JER, and limited statistics in the CRs.

The experimental uncertainties on JES and JER are obtained by a dedicated analysis, introduced in Section 5.2.3 and depend on the  $p_T$  and  $\eta$  of the jets. A scale and resolution uncertainties are also applied  $E_T^{\text{miss}}$  soft-track term. Uncertainties associated with the jet mass scale (JMS) and mass resolution (JMR) are also assigned to the **2jB-1600** and **2jB-2400** due to the requirements on the masses of large- $R$  jets and they are discussed in Section 7.12. Uncertainties on  $b$ -tagging in CRW and CRT are included as well. The uncertainties related to the leptons and photon efficiency reconstruction are found to have a limited impact and therefore are neglected for all regions.

The theoretical uncertainties from the modeling of the background processes are estimated either by comparing samples generated with two different Monte Carlo generators or by comparing samples from the same generator with modified scales.

The uncertainties on the modeling of vector-boson processes are estimated by increasing and decreasing the following parameters:

- Renormalisation, factorisation and resummation scale parameters are multiplied by 0.5 and 2.
- Nominal CKKW (Section 4.1.5) matrix-element-parton-shower matching scale parameter is varied from nominal value of 20 GeV to 15 and 30 GeV.

The uncertainty on the  $k$  factor obtained to normalize the  $\gamma$ +jets simulation samples is included as well.

The uncertainties in the modeling of  $t\bar{t}$  production is studied by comparing the samples generated with POWHEG-BOX and MG5\_AMC@NLO. The choice of the PERUGIA 2012 tune in the  $t\bar{t}$  production is studied by comparing the nominal sample with sample tuned with A14 shower tune. The uncertainties arising with PDF modelling of  $t\bar{t}$  production are found to be negligible.

The uncertainties on the diboson background are calculated by varying the matching, factorisation, and renormalisation scales as well as the parton distribution functions set, and accounting a 6% of uncertainty on the total cross section.

The uncertainties associated with the jet smearing method used for the multi-jet background estimates are treated by applying a uniform 100% uncertainty on the multi-jet final yield in all the SRs.

The extrapolation uncertainties account for the statistical uncertainty on the Monte Carlo samples using a Poissonian uncertainty ( $\sqrt{N_{MC}}$ ) and include the statistical uncertainty in the control regions as well.

#### *Treatment in the Likelihood Fit*

The systematic uncertainties are accounted in the likelihood fit by using product of Gaussian probability density functions, each of them being parametrised by a nuisance parameter. The systematic uncertainties can be treated in the fit in the following ways:

- Fully correlated across the different regions and the different physics processes, as for example the uncertainty on luminosity.
- Fully correlated across the different regions but independent per process, e.g. theoretical uncertainties.
- Fully uncorrelated variables with one parameter per bin, e.g. uncertainties due to limited statistics of the simulation samples.

A summary of the systematic uncertainties considered in the Likelihood fit with their characteristic scale, correlation treatment in the fit, and eventual comments is given in Table 16.

| Name                                     | Process                 | Treatment              | Comment                                                                                          |
|------------------------------------------|-------------------------|------------------------|--------------------------------------------------------------------------------------------------|
| Luminosity                               | All                     | Fully correlated       | $\pm 4.1\%$                                                                                      |
| Pileup                                   |                         | Fully correlated       | See Section <a href="#">7.3.3</a>                                                                |
| MC statistics                            |                         | Uncorrelated           |                                                                                                  |
| CR norm. factor $\mu$                    | W/Z/ $\gamma$ +jets/top | Uncorrelated           |                                                                                                  |
| Object modelling                         |                         |                        |                                                                                                  |
| Jet energy scale (JES)                   | All                     | Fully correlated       | Only in boosted boson SR                                                                         |
| Jet energy resolution (JER)              |                         |                        |                                                                                                  |
| Jet mass scale (JMS)                     |                         |                        |                                                                                                  |
| Jet mass resolution (JMR)                |                         |                        |                                                                                                  |
| $E_T^{\text{miss}}$ soft term scale      |                         |                        | Only in boosted boson SR                                                                         |
| $E_T^{\text{miss}}$ soft term resolution |                         |                        |                                                                                                  |
| b-tagging efficiency (b/c/light)         |                         |                        | Only in CRW and CRT                                                                              |
| Physics process modelling                |                         |                        |                                                                                                  |
| Cross section and acceptance             | Diboson                 | Uncorrelated           | SHERPA-1.4.0 scale variation<br>POWHEG vs aMC@NLO<br>High vs Low<br>PYTHIA6 P2011 vs PYTHIA8 A14 |
| Scale variation                          | W/Z/ $\gamma$ +jets     | Correlated per process |                                                                                                  |
| Generator comparison                     | $t\bar{t}$              | Correlated per process |                                                                                                  |
| Radiation                                | $t\bar{t}$              |                        |                                                                                                  |
| Parton shower tunes                      | $t\bar{t}$              |                        |                                                                                                  |
| $\kappa$ factor                          | Z/ $\gamma$             | Uncorrelated           |                                                                                                  |
| Jet Smearing                             | Multijet                | Uncorrelated           | $\pm 100\%$                                                                                      |

Table 16: Summary of systematic uncertainties included in the likelihood fit.

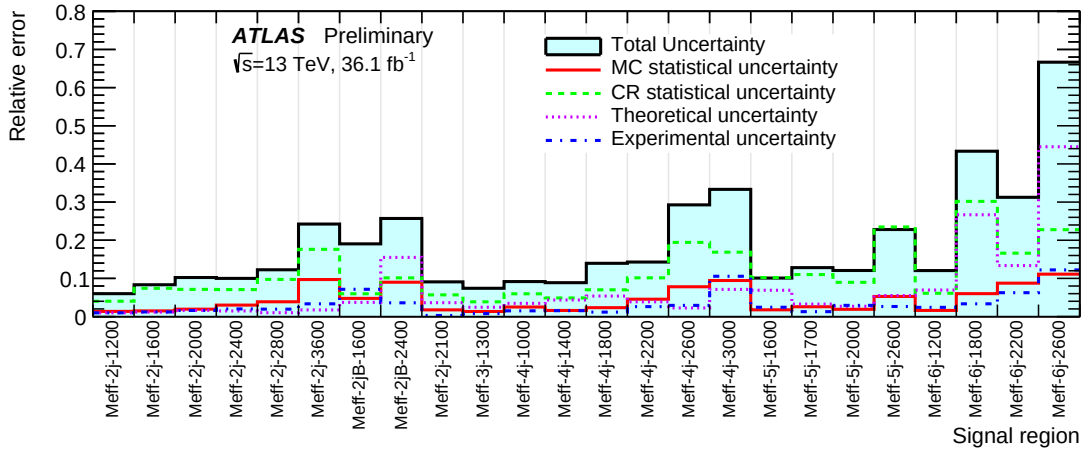


Figure 70: Breakdown of the largest systematic uncertainties and their impact on the background estimates for the presented analysis. The potential correlation between individual uncertainties is here not taken in account, such that the total background uncertainty is not necessarily the sum in quadrature of each contribution.

The breakdown of the largest background uncertainties for each of the SRs is depicted in Figure 70. A numeric analysis of the systematic uncertainties is given in Section 7.13.4

### 7.10.2 Uncertainties on Signal

The experimental and theoretical uncertainties on the event yield of the SUSY simplified models used in the analysis are taken in account in the model-dependent limit calculation.

#### *Signal Experimental Uncertainties*

The experimental uncertainties affecting the acceptance of the SUSY models in the different SRs, as the JES, JER,  $E_T^{\text{miss}}$ , JMS, JMR, are evaluated with the same methods as for the background processes. The JMS/JMR are taken in account only in the boosted SRs and they will be discussed later in Section 7.12. The uncertainties are included in the fit together with the uncertainties on the background. Typically, experimental uncertainties on signal are less than a few percent. Therefore, it does not affect much the final results. Typical size of systematic uncertainties for a selection of signal regions are listed in Table 17.

|           |                              | Systematics (%) |                    |       |       |                     |              |       |
|-----------|------------------------------|-----------------|--------------------|-------|-------|---------------------|--------------|-------|
| Region    | Signal                       | JER             | JES (3 parameters) |       |       | $E_T^{\text{miss}}$ |              |       |
|           |                              |                 | 1                  | 2     | 3     | Resolution 1        | Resolution 2 | Scale |
| SR2j-1200 | SS-direct<br>(1000,500)      | +0.37           | +1.89              | +1.69 | +0.24 | +0.05               | +0.36        | +0.12 |
|           |                              | -0              | -1.73              | -1.91 | -0    | -0                  | -0           | -0.06 |
| SR2j-2400 | SS-direct<br>(1500,300)      | +0              | +1.91              | +2.56 | +0.43 | +0                  | +0.11        | +0.05 |
|           |                              | -0.01           | -1.20              | -1.81 | -0.39 | -0.05               | -0           | -0    |
| SR4j-3000 | GG-direct<br>(2000,0)        | +0              | +1.67              | +1.82 | +0.77 | +0.13               | +0           | +0.07 |
|           |                              | -0.59           | -2.68              | -2.18 | -0.85 | -0                  | -0.07        | -0    |
| SR6j-2200 | GG-onestep<br>(2025,1025,25) | +0              | +1.50              | +0.45 | +0.11 | +0.00               | +0           | +0.11 |
|           |                              | -0.88           | -1.84              | -0.56 | -0.29 | -0                  | -0.06        | -0    |

Table 17: Selection of experimental systematics uncertainties (%) on selected signal points in various signal regions.

### 7.10.3 Signal Cross Section Uncertainty

The uncertainties on the cross section of the signals affect the overall normalisation of the SUSY models in the SRs. The uncertainty is estimated by:

- varying the factorisation and renormalisation scale by a factor 0.5 and 2;
- varying the PDF set (NNPDF2.3LO [110]), and the strong coupling constant  $\alpha_S$  and subsequently calculating the cross section for each variation.

The limit on the visible cross section is calculated using the central value of the cross section. The cross section uncertainties are only used to provide an error band on the observed limit.



## 7.11 SIGNAL THEORY UNCERTAINTIES

In very compressed signal points, where  $m_{\tilde{g}/\tilde{q}}$  is very close to  $m_{\text{LSP}}$ , the jets originating from  $\tilde{g}/\tilde{q}$  decays are very soft. The analysis selection cuts can be fulfilled only when hard initial-state radiation (ISR) jets are emitted. Hence, a strong dependence of the signal acceptance on the modeling of radiation effect in the MC simulation is present. Extra uncertainties have to be included to take into account these effects.

In other cases, the presence of final state radiation (FSR) requires extra uncertainties on the theory prediction of the number of SUSY events to be considered.

The uncertainties related to the ISR and FSR are evaluated by :

1. varying PYTHIA8 tunes (VAR3c) [214] accounting for extra-jet production;
2. varying the matching scales relating Matrix Element radiations in MADGRAPH5 with parton shower radiations done in PYTHIA8 by 0.5 and 2;

The resulting effects on the signal efficiency and acceptance have been studied on the gluino-pair production simplified model as function of the mass splitting between the produced sparticle and the LSP,  $\Delta m = m(\tilde{g}) - m(\tilde{\chi}_1^0)$  for channels with various jet multiplicities. Preliminary studies have shown that only the first variation gives appreciable contributions.

There is an overlap between the theory uncertainties and those used for the signal cross sections described in Section 7.10.3. Therefore, in the following study the focus is on the change in shape of the most important differential distributions, e.g.  $m_{\text{eff}}$ , and the resulting impact on the acceptance in the various SRs when variations are applied in the signal sample simulation. However, the impact on the overall normalisation differences is already covered by the signal cross section uncertainties.

The study proceeds as follows:

- Signal samples with the varied VAR3c parameters have been generated with MADGRAPH5+PYTHIA8 at *truth* level, where each object is reconstructed directly from the simulated process.
- For each signal region, a set of 4 signal points have been generated with increasing  $\Delta m = 10, 50, 100, 200$  GeV.
- After applying the SRs selection, the variation in signal acceptance is calculated with respect to the nominal sample (i.e. generated with no variations) and symmetrized.<sup>5</sup>

<sup>5</sup> Because of the lack of statistics of signal events in some of the SRs, the cut on  $m_{\text{eff}}$  has been loosened to allow more statistic. The lower  $m_{\text{eff}}$  cut value has been chosen by looking at the so-called *cumulative*  $m_{\text{eff}}$ , defined as the distribution where the  $n$ -th bin is the integral of the  $m_{\text{eff}}$  distribution in the first  $(n, n_{\text{max}})$  bins.

- The uncertainty is parametrized with functions:

$$\delta_{\text{syst}} = a \cdot e^{-b \cdot \Delta m + c} \quad (107)$$

and the exact values of the parameter set  $(a, b, c)$  in Equation (107) are found through a fit to signal regions with a looser cut on  $m_{\text{eff}}$ .

A selection of the results are shown in Figure 71. This theory uncertainty accounts in general for 20% of the signal acceptance for low  $\Delta m$ , in the so-called *compressed* regions of simplified models parameter space, while it is almost negligible at  $\Delta m > 200$  GeV.

The systematic uncertainties according to the parametrization are applied to the signal yield for each signal region.

## 7.12 SYSTEMATIC UNCERTAINTIES IN BOOSTED ANALYSIS

In addition to the set of systematic uncertainties assigned to the background and signal processes in the  $m_{\text{eff}}$ -based signal regions, supplementary uncertainties on jet mass scale (JMS) and jet mass resolution (JMR) are applied in the Boosted analysis. This is due to the use of requirements on the invariant masses of large-radius jets in the Boosted signal regions **2jB-1600** and **2jB-2400**. The effect of the additional systematics is visible in Figure 70, where a broader uncertainty is associated to the **2jBs** regions.

### 7.12.1 Jet Mass Scale

The large-R jets of cone 1.0 come out of the reclustering algorithm described in Section 5.3. In the boosted scenario, where cuts on jet mass around the  $W/Z$  masses are placed, quite few subjets (most of the cases only 1 or 2) constitute the reclustered jet. This feature can be observed in the bottom pictures of Figure 58 and 60. The less subjets are present, the bigger role plays the JMS uncertainty, as the subjets contribute more to the final reclustered jet mass. In the opposite situation with many subjets, the mass mainly depends on the already considered JES.

The strategy to get the evaluation on the JMS uncertainty for reclustered jets with 1.0 cone is to apply a variation to the input small-R jets. During the reclustering, the uncertainty automatically propagates from the inputs to the resulting reclustered jets.

The JMS estimation relies on a method based on studying the ratio  $r_{\text{track}}^m = m_{\text{calo}}/m_{\text{track}}$ , where  $m_{\text{calo}}$  is the calorimeter-based jet mass and  $m_{\text{track}}$  is the invariant mass of the four-vector sum of tracks associated to the large-radius (1.0) calorimeter jet. The method is fully described in Reference [215]. Four variations are obtained and applied to the input jets.

#### *JMS for Signal*

In the signal case, a study has been performed on the signal points of the  $\tilde{q}\tilde{q}(\tilde{g}\tilde{g})$ -onestep signal sample used for the **2jB-1600(2jB-2400)** signal

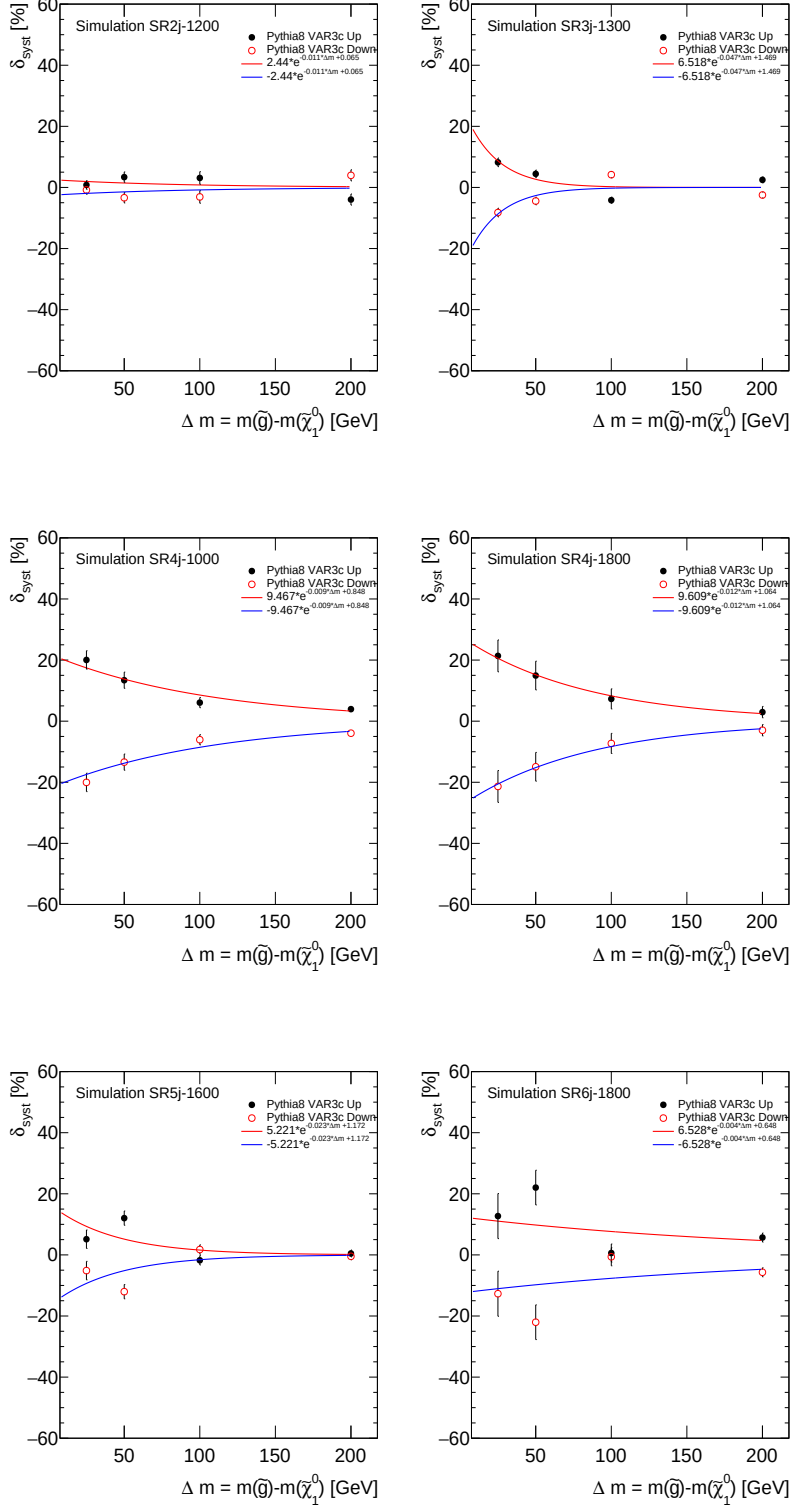


Figure 71: Impact of A14\_NNPDF tune variations used in PYTHIA8 on signal acceptance in the different signal regions for a simplified model with gluino pair production followed by a direct decay to two quarks and a  $\tilde{\chi}_1^0$ . The relative signal uncertainty  $\delta_{\text{syst}}$  is shown as a function of  $\Delta m = m(\tilde{g}) - m(\tilde{\chi}_1^0)$ . The lines show the parametrizations used to compute the uncertainties on signal acceptance.

regions optimisation: (1100, 1050, 60) and (1700, 1690, 60). Signal point samples has been produced with the JMS variation applied. The overall JMS systematic uncertainty is then obtained by adding in quadrature the uncertainties of the four components in the signal regions **2jBs**. The results give a JMS uncertainty on the signal acceptance on the order of 2%, which is used conservatively as value for all the signal points of the models of interest in the boosted analysis.

### *JMS for Background*

The JMS uncertainty estimation for the background is obtained calculating the variation on the background transfer factors from CRW, CRY, CRT, and on the Diboson background, whose contribution in the SRs is taken directly from the MC normalisation. The variation results are summarised in Table 18.

|                         | <b>2jB-1600</b> | <b>2jB-2400</b> |
|-------------------------|-----------------|-----------------|
| Uncertainties on Signal |                 |                 |
| GG-onestep              | 2%              | 2%              |
| SS-onestep              | 2%              | 2%              |
| Uncertainties on TF     |                 |                 |
| W+jets                  | 1.95 %          | 4.72%           |
| Z+jets                  | 1.73 %          | 4.50 %          |
| Top                     | 6.98%           | 5.09%           |
| Uncertainties on MC     |                 |                 |
| Diboson                 | 2.85 %          | 7.96 %          |

Table 18: JMS percentage uncertainties on signal acceptance, transfer factors for the W,Z,Top background samples and on SRs acceptance for Diboson sample in **2jB-1600** and **2jB-2400**.

### 7.12.2 *Jet Mass Resolution*

The strategy for assessing the jet mass resolution uncertainty on reclustered large-R jets (with 1.0 cone) in the boosted analysis relies firstly on calculating the MC resolution of the large-R jets and then smearing the jet mass such that a Gaussian distribution with a fixed value (20%) width is obtained.

The mass response sigma of the reclustered jets (RT) can be estimated as:

$$\sigma_{RT} = |M_{RTjet}^{truth} - M_{RTjet}| \quad (108)$$

where  $M_{RTjet}^{truth}$  is the mass of the "Truth Reclustered Jets", defined as the small-R jets at truth level matched to the reconstructed small-R

| GG-onestep |          |          | SS-onestep |          |          |
|------------|----------|----------|------------|----------|----------|
| x          | 2jB-1600 | 2jB-2400 | x          | 2jB-1600 | 2jB-2400 |
| 0.9        | 6%       | 5%       | 0.9        | 4%       | 4%       |
| 0.95       | 3%       | 3%       | 0.95       | 4%       | 2%       |
| 1          | 7%       | 8%       | 1          | 7%       | 7%       |

Table 19: JMR percentage uncertainties on signal samples for **2jB-1600** and **2jB-2400** in three different mass splitting scenarios.

| W+jets (TF) |          |
|-------------|----------|
| 2jB-1600    | 2jB-2400 |
| 3%          | 11%      |

Table 20: JMR percentage uncertainties on W+jets background transfer factor from CRW to **2jB-1600** and **2jB-2400**.

jets input to the reclustering algorithm. In order to implement a 20% smearing on the mass, we impose that the smeared width is:

$$\sigma_{\text{new}}^2 = 1.2 \cdot \sigma_{\text{RT}}^2 = \sigma_{\text{RT}}^2 + \sigma_{\text{smeared}}^2 \quad (109)$$

So that it is possible to smear the mass resolution with a Gaussian distribution with mean and width:

$$\begin{aligned} \mu_{\text{smeared}} &= M_{\text{RTjet}} \\ \sigma_{\text{smeared}} &= \sqrt{1.2 - 1} \cdot \sigma_{\text{RT}} = 0.66 \cdot \sigma_{\text{RT}} \end{aligned} \quad (110)$$

In order to estimate the JMR uncertainty for the signal, a study has been performed on three points of the  $\tilde{g}\tilde{g}/\tilde{q}\tilde{q}$ -pair production with one-step decay simplified model with same  $m_{\tilde{g}} = 1800$  GeV ( $m_{\tilde{q}} = 1100$  GeV) and three different  $x$  parameters:  $\sim 0.95$ ,  $\sim 0.9$ ,  $\sim 1$ . The results are summarized in Table 19.

The study of the JMR uncertainty on the background transfer factor (TF) has been performed on the W+jets background, which is the most dominant one. The uncertainties on the TF of the other background processes are assumed to be of the similar order, so that the same JMR value is used for all the TFs. Results are shown in Table 20.

As final estimation, a common uncertainty of 7% in both of the **SR2jB** has been taken in account for the signal acceptance, while an uncertainty of 3%(11%) in the **SR2jB-1600(SR2jB-2400)** has been applied on the transfer factors of the background processes.

## 7.13 FIT RESULTS

The statistical procedure used to obtain the results of the analysis is composed of three type of fits, as described in Section 6.6. A general discussion on the results from the background-only fit is in Section 7.13.1,

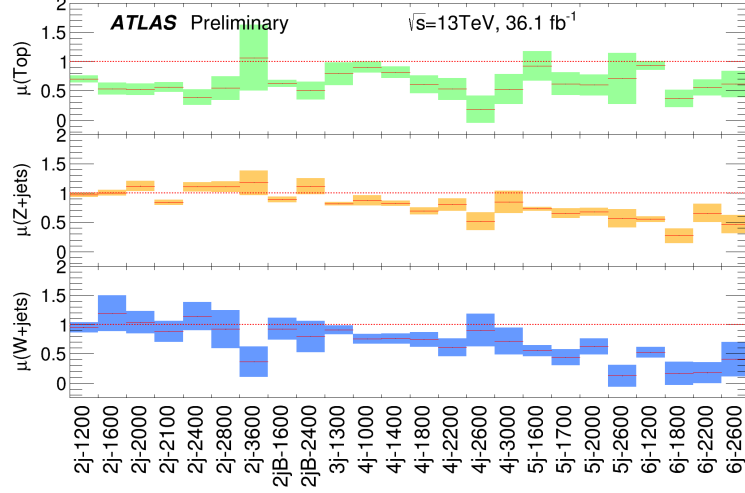


Figure 72: Fitted normalization factor per process as a function of the channel considered in the 0-lepton search. The dashed horizontal lines at 1 correspond to pure Monte Carlo estimates with the vertical size of the colored regions corresponding to the total uncertainty on each background source.

while results in VRs and SRs are discussed in Section 7.13.2 and Section 7.13.3. A dedicated discussion on the results from the boosted analysis is in Section 7.13.5.

#### 7.13.1 Background-only Fit Results

The normalization factors obtained per process in each of the control region from the background-only fit, as defined in Eq. (79) is shown in Figure 72. The factors are indicated as  $\mu$ . Some observations on specific trends can be made:

- The normalization factor for Top background tends to become smaller with increasing requirements on the  $m_{\text{eff}}$  variable. This follows the indication of Top MC simulation to generally have an harder kinematics than in observed events.
- The normalization factors for W+jets and Z+jets processes are generally stable but tend to decrease with the increase of the requirements on  $N_{\text{jets}}$ , reflecting the fact that SHERPA produces a harder jet spectrum than measured.
- The pseudo-data used to estimate the multijet background coming from jet-smearing procedure does not have a corresponding luminosity. Prior to the fit, preliminary normalisation factors are obtained by simply normalising the pseudo-data in CRQ for each signal region.

### 7.13.2 Results in Validation Regions

In order to test the robustness of the background estimate obtained with the background-only fit, the results have been extrapolated to the validation regions defined in Section 6.5.1. The agreement between the expected and observed number of events in each of the validation regions is quantified by calculating the pull  $P$  for each region, defined as the numbers of observed and expected events, expressed as fractions of the  $1\sigma$  deviation uncertainties on the latter:

$$P = \frac{n_{\text{obs}} - n_{\text{pred}}}{\sigma_{\text{tot}}} \quad (111)$$

where  $\sigma_{\text{tot}} = \sigma_{\text{stat}} \oplus \sigma_{\text{pred}}$ , with  $\sigma_{\text{pred}}$  the uncertainty coming from the fit and  $\sigma_{\text{stat}}$  the standard deviation of a Poisson distribution with mean  $n_{\text{pred}}$ . So defined, the pull measures how many  $\sigma$ 's the observed number of events in a validation region differs from the fit prediction. The pulls in the validation regions associated with each of the 22+2 signal regions are shown in Figure 73. Most of the observed results lie within  $1.5\sigma$  of the background expectations, which is a clear indication of a good agreement between observation and prediction. Only a larger discrepancy of  $2.4\sigma$  is observed in the VRWMf region for **SR5j-2600**. This effect can be treated as a statistical fluctuation, given the lack of statistics which this region suffer of.

Having tested the agreement in the validation regions, the background estimate coming from the background-only can be valued as reliable and the signal regions can therefore be studied.

### 7.13.3 Results in Signal Regions

The distribution of the final selective variable in the 0-lepton analysis, the  $m_{\text{eff}}$ , for data and SM background in all the 22+2 signal regions before the background fit and prior to the cut on the  $m_{\text{eff}}$  itself, are shown in Figures 75-78. The expected SM background distributions are obtained from Monte Carlo samples normalised with their cross sections to the integrated luminosity, while the multijet is taken from the jet-smearing method. The distribution of the benchmark SUSY models used for the optimisation of the various signal regions are overlaid in order to show the typical expected SUSY signal kinematics.

The distributions shows a general agreement between the SM background and the observed data. However, it can be seen how the difference between data and simulation tends to increase at higher  $m_{\text{eff}}$  values, which is the primary reason for the treatment of the SM background estimate via control regions. By fitting in the control regions, the systematic discrepancies between observation and expectation can therefore be taken into account.

The summary of the number of observed data events and the expected background yields, both before and after the fit, is given in Table 21. For each signal region, the model-independent limits on the visible production cross section, the expected and observed upper limits on the visible





| Signal Region                                               | 2j-1200                          | 2j-1600                          | 2j-2000                         | 2j-2400                        | 2j-2800                        | 2j-3600                             | 2j-B1600                       | 2j-B2400                               |
|-------------------------------------------------------------|----------------------------------|----------------------------------|---------------------------------|--------------------------------|--------------------------------|-------------------------------------|--------------------------------|----------------------------------------|
| MC expected events                                          |                                  |                                  |                                 |                                |                                |                                     |                                |                                        |
| Diboson                                                     | 28.17                            | 14.37                            | 7.02                            | 3.09                           | 0.86                           | 0.18                                | 2.94                           | 0.53                                   |
| Z/,*+jets                                                   | 346.37                           | 140.61                           | 54.13                           | 24.23                          | 10.22                          | 2.28                                | 13.84                          | 2.45                                   |
| W+jets                                                      | 142.39                           | 47.49                            | 18.33                           | 8.23                           | 3.37                           | 1.11                                | 5.16                           | 0.71                                   |
| Top                                                         | 21.40                            | 5.84                             | 2.54                            | 1.13                           | 0.32                           | 0.04                                | 0.86                           | 0.10                                   |
| Fitted background events                                    |                                  |                                  |                                 |                                |                                |                                     |                                |                                        |
| Diboson                                                     | 28 ± 4                           | 14.4 ± 2.3                       | 7.0 ± 1.1                       | 3.1 ± 0.5                      | 0.86 ± 0.17                    | 0.18 ± 0.07                         | 2.9 ± 0.7                      | 0.53 ± 0.1                             |
| Z/,*+jets                                                   | 337 ± 19                         | 141 ± 10                         | 61 ± 8                          | 26.8 ± 3.1                     | 11.4 ± 1.4                     | 2.7 ± 0.7                           | 12.3 ± 1.8                     | 2.7 ± 0.5                              |
| W+jets                                                      | 136 ± 24                         | 57 ± 16                          | 19 ± 5                          | 9.4 ± 2.6                      | 3.1 ± 1.1                      | 0.4 ± 0.31                          | 4.8 ± 2.8                      | 0.6 ± 0.6                              |
| Top                                                         | 15 ± 4                           | 3.1 ± 1.7                        | 1.34 ± 1.0                      | 0.4 ± 0.4                      | 0.18 ± 0.15                    | 0.04 ± 0.04                         | 0.5 ± 0.5                      | 0.05 <sup>+0.57</sup> <sub>-0.05</sub> |
| Multi-jet                                                   | 1.8 ± 1.8                        | 0.34 ± 0.34                      | —                               | —                              | —                              | —                                   | —                              | —                                      |
| Total bkg                                                   | 517 ± 31                         | 216 ± 18                         | 88 ± 9                          | 40 ± 4                         | 15.5 ± 1.9                     | 3.3 ± 0.8                           | 21 ± 4                         | 3.9 ± 1.0                              |
| Observed                                                    | 582                              | 204                              | 70                              | 33                             | 17                             | 5                                   | 23                             | 2                                      |
| $\langle \epsilon \text{ff} \rangle_{\text{obs}}^{95}$ [fb] | 3.6                              | 1.00                             | 0.42                            | 0.30                           | 0.32                           | 0.20                                | 0.42                           | 0.11                                   |
| $S_{\text{obs}}^{95}$                                       | 131                              | 36                               | 15                              | 11                             | 11                             | 7.1                                 | 15.1                           | 4.1                                    |
| $S_{\text{exp}}^{95}$                                       | 78 <sup>+33</sup> <sub>-21</sub> | 43 <sup>+17</sup> <sub>-12</sub> | 24 <sup>+10</sup> <sub>-6</sub> | 15 <sup>+7</sup> <sub>-4</sub> | 10 <sup>+4</sup> <sub>-3</sub> | 5.4 <sup>+2.0</sup> <sub>-1.5</sub> | 13 <sup>+5</sup> <sub>-3</sub> | 5.0 <sup>+2.3</sup> <sub>-1.1</sub>    |
| p <sub>0</sub> (Z)                                          | 0.06 (1.53)                      | 0.50 (0.00)                      | 0.50 (0.00)                     | 0.50 (0.00)                    | 0.33 (0.43)                    | 0.19 (0.87)                         | 0.37 (0.34)                    | 0.50 (0.00)                            |

| Signal Region                                               | 2j-2100                         | 3j-1300                                | 4j-1000     | 4j-1400                         | 4j-1800                        | 4j-2200                        | 4j-2600                                | 4j-3000                             |
|-------------------------------------------------------------|---------------------------------|----------------------------------------|-------------|---------------------------------|--------------------------------|--------------------------------|----------------------------------------|-------------------------------------|
| MC expected events                                          |                                 |                                        |             |                                 |                                |                                |                                        |                                     |
| Diboson                                                     | 12.87                           | 34.43                                  | 6.56        | 13.18                           | 4.40                           | 2.14                           | 0.35                                   | 0.06                                |
| Z/,*+jets                                                   | 115.70                          | 265.30                                 | 59.58       | 99.18                           | 32.76                          | 11.95                          | 4.05                                   | 1.34                                |
| W+jets                                                      | 33.90                           | 105.92                                 | 28.91       | 51.75                           | 14.57                          | 4.49                           | 1.66                                   | 0.61                                |
| Top                                                         | 4.96                            | 36.08                                  | 42.86       | 41.67                           | 7.64                           | 1.71                           | 0.63                                   | 0.21                                |
| Fitted background events                                    |                                 |                                        |             |                                 |                                |                                |                                        |                                     |
| Diboson                                                     | 13 ± 5                          | 34 ± 6                                 | 6.6 ± 1.2   | 13.2 ± 2.2                      | 4.4 ± 0.9                      | 2.1 ± 0.5                      | 0.35 ± 0.08                            | 0.06 ± 0.03                         |
| Z/,*+jets                                                   | 97 ± 8                          | 218 ± 20                               | 52 ± 7      | 82 ± 9                          | 23 ± 4                         | 9.6 ± 1.9                      | 2.1 ± 0.7                              | 1.1 ± 0.5                           |
| W+jets                                                      | 30 ± 9                          | 96 ± 18                                | 22 ± 7      | 39 ± 9                          | 11 ± 5                         | 2.74 ± 1.0                     | 1.5 ± 0.9                              | 0.43 ± 0.33                         |
| Top                                                         | 2.8 ± 1.6                       | 28 ± 10                                | 39 ± 7      | 33 ± 10                         | 4.7 ± 3.2                      | 0.9 ± 0.5                      | 0.12 <sup>+0.15</sup> <sub>-0.12</sub> | 0.11 ± 0.1                          |
| Multi-jet                                                   | 0.15 ± 0.15                     | 0.79 <sup>+0.80</sup> <sub>-0.79</sub> | 0.20 ± 0.20 | 0.4 ± 0.4                       | —                              | —                              | —                                      | —                                   |
| Total bkg                                                   | 143 ± 13                        | 378 ± 28                               | 120 ± 11    | 169 ± 15                        | 43 ± 6                         | 15.4 ± 2.2                     | 4.0 ± 1.2                              | 1.8 ± 0.6                           |
| Observed                                                    | 180                             | 405                                    | 135         | 179                             | 53                             | 23                             | 4                                      | 2                                   |
| $\langle \epsilon \text{ff} \rangle_{\text{obs}}^{95}$ [fb] | 2.0                             | 2.5                                    | 1.3         | 1.5                             | 0.85                           | 0.47                           | 0.17                                   | 0.12                                |
| $S_{\text{obs}}^{95}$                                       | 70                              | 91                                     | 47          | 55                              | 31                             | 17                             | 6.1                                    | 4.4                                 |
| $S_{\text{exp}}^{95}$                                       | 37 <sup>+14</sup> <sub>-9</sub> | 69 <sup>+27</sup> <sub>-17</sub>       | 36 ± 10     | 40 <sup>+16</sup> <sub>-9</sub> | 21 <sup>+8</sup> <sub>-5</sub> | 10 <sup>+5</sup> <sub>-3</sub> | 6.0 <sup>+2.0</sup> <sub>-1.8</sub>    | 4.3 <sup>+1.7</sup> <sub>-1.0</sub> |
| p <sub>0</sub> (Z)                                          | 0.02 (2.14)                     | 0.20 (0.85)                            | 0.13 (1.13) | 0.11 (1.24)                     | 0.07 (1.45)                    | 0.07 (1.45)                    | 0.50 (0.00)                            | 0.44 (0.14)                         |

| Signal Region                                               | 5j-1600                          | 5j-1700                        | 5j-2000                        | 5j-2600                                | 6j-1200                          | 6j-1800                                | 6j-2200                                | 6j-2600                                |
|-------------------------------------------------------------|----------------------------------|--------------------------------|--------------------------------|----------------------------------------|----------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| MC expected events                                          |                                  |                                |                                |                                        |                                  |                                        |                                        |                                        |
| Diboson                                                     | 10.29                            | 5.61                           | 6.59                           | 0.73                                   | 19.00                            | 0.15                                   | 0.26                                   | 0.09                                   |
| Z/,*+jets                                                   | 55.12                            | 30.42                          | 49.38                          | 7.32                                   | 103.92                           | 3.29                                   | 1.26                                   | 0.76                                   |
| W+jets                                                      | 41.39                            | 15.21                          | 18.42                          | 2.60                                   | 78.02                            | 2.15                                   | 0.70                                   | 0.47                                   |
| Top                                                         | 44.63                            | 11.71                          | 9.77                           | 0.75                                   | 139.99                           | 4.31                                   | 0.61                                   | 0.36                                   |
| Fitted background events                                    |                                  |                                |                                |                                        |                                  |                                        |                                        |                                        |
| Diboson                                                     | 10.3 ± 1.8                       | 5.61 ± 1.0                     | 6.6 ± 1.2                      | 0.73 ± 0.13                            | 19.0 ± 3.2                       | 0.15 ± 0.11                            | 0.26 ± 0.07                            | 0.09 <sup>+0.11</sup> <sub>-0.09</sub> |
| Z/,*+jets                                                   | 40 ± 5                           | 20 ± 4                         | 34 ± 6                         | 4.2 ± 1.3                              | 58 ± 10                          | 0.9 ± 0.5                              | 0.8 ± 0.4                              | 0.35 ± 0.22                            |
| W+jets                                                      | 23 ± 7                           | 6.7 ± 2.4                      | 11.6 ± 3.1                     | 0.32 <sup>+0.41</sup> <sub>-0.32</sub> | 41 ± 20                          | 0.36 <sup>+0.59</sup> <sub>-0.36</sub> | 0.12 <sup>+0.18</sup> <sub>-0.12</sub> | 0.19 <sup>+0.27</sup> <sub>-0.19</sub> |
| Top                                                         | 42 ± 11                          | 7.2 ± 2.5                      | 5.9 ± 2.3                      | 0.5 ± 0.5                              | 130 ± 23                         | 1.6 ± 1.2                              | 0.35 ± 0.24                            | 0.22 <sup>+0.39</sup> <sub>-0.22</sub> |
| Multi-jet                                                   | 4 ± 4                            | —                              | —                              | —                                      | 0.72 ± 0.72                      | —                                      | —                                      | —                                      |
| Total bkg                                                   | 119 ± 12                         | 39 ± 5                         | 58 ± 7                         | 5.7 ± 1.3                              | 249 ± 30                         | 3.0 ± 1.3                              | 1.6 ± 0.5                              | 0.8 ± 0.6                              |
| Observed                                                    | 122                              | 45                             | 52                             | 10                                     | 250                              | 9                                      | 3                                      | 1                                      |
| $\langle \epsilon \text{ff} \rangle_{\text{obs}}^{95}$ [fb] | 1.03                             | 0.60                           | 0.48                           | 0.30                                   | 2.1                              | 0.35                                   | 0.16                                   | 0.11                                   |
| $S_{\text{obs}}^{95}$                                       | 37                               | 22                             | 17                             | 10.7                                   | 74                               | 13                                     | 5.6                                    | 4.1                                    |
| $S_{\text{exp}}^{95}$                                       | 35 <sup>+12</sup> <sub>-11</sub> | 17 <sup>+7</sup> <sub>-5</sub> | 20 <sup>+8</sup> <sub>-5</sub> | 7.1 <sup>+2.9</sup> <sub>-2.1</sub>    | 61 <sup>+23</sup> <sub>-14</sub> | 8.7 <sup>+2.8</sup> <sub>-1.8</sub>    | 4.2 <sup>+1.5</sup> <sub>-0.6</sub>    | 3.5 <sup>+1.5</sup> <sub>-0.2</sub>    |
| p <sub>0</sub> (Z)                                          | 0.35 (0.37)                      | 0.22 (0.78)                    | 0.50 (0.00)                    | 0.10 (1.25)                            | 0.50 (0.00)                      | 0.08 (1.43)                            | 0.16 (1.00)                            | 0.19 (0.89)                            |

Table 21: Numbers of events observed in the signal regions compared with background expectations obtained from the fits. Empty cells (indicated by a ‘-’) correspond to estimates lower than 0.01. The p-values (p<sub>0</sub>) give the probabilities of the observations being consistent with the estimated backgrounds. For an observed number of events lower than expected, the p-value is truncated at 0.5. Between parentheses, p-values are also given as the number of equivalent Gaussian standard deviations (Z). Also shown are 95% CL upper limits on the visible cross-section ( $\langle \epsilon \sigma \rangle_{\text{obs}}^{95}$ ), the visible number of signal events ( $S_{\text{obs}}^{95}$ ) and the number of signal events ( $S_{\text{exp}}^{95}$ ) given the expected number of background events (and  $\pm 1\sigma$  excursions of the expectation).

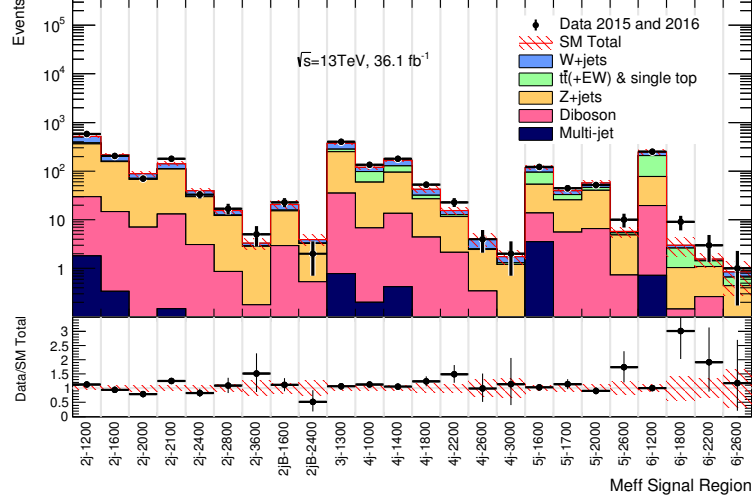


Figure 74: Comparison of the observed and expected event yields as a function of signal region in the 0-lepton search. The background predictions are those obtained from the background-only fits, presented in Table 21. The bottom graph shows the ratio of observed data yields to the total predicted background.

The overall uncertainty as percentage on the expected yield ranges from 6.01% in **SR2j-1200** to 66.68% in **SR6j-2600**, as can be observed from the fit result Table 21 ("Total bkg"). The breakdown of the different fractional contributions, as depicted in Figure 70, shows the major impact of the uncertainties on the normalisation factors, "CR statistical Uncertainty" or  $\Delta\mu$ , covering both statistical uncertainties in the control regions and uncertainties related to the specific background, e.g. on the b-tagging in CRT and on the  $\gamma$ +jets normalization factor  $\kappa$ . It can be noted that a loose selection applied tend to minimize the theoretical uncertainties and the impact of the statistical fluctuation on the control regions, leading to a lower systematic uncertainty contribution in the corresponding signal regions, viceversa tighter requirements cause the opposite.

The experimental uncertainties such as the resolution and scale of jets and  $E_T^{\text{miss}}$ , have in most signal regions a smaller impact compared to the theoretical uncertainties and the uncertainties on the transfer factors.

#### 7.13.5 Boosted Analysis Results

The distribution of the  $m_{\text{eff}}$  variable in the boosted signal regions **SR2jB-1600** and **SR2jB-2400** prior the background fit can be found in the bottom pictures in Figure 78. The signal regions results to be well-modeled in  $m_{\text{eff}}$  distribution, with no particular mismodeling present.

The detailed background-only fit results in the VRs and the SRs are reported beside the other  $m_{\text{eff}}$ -based SRs in Figure 73 and in Table 21, respectively. The pulls show an overall good agreement in the

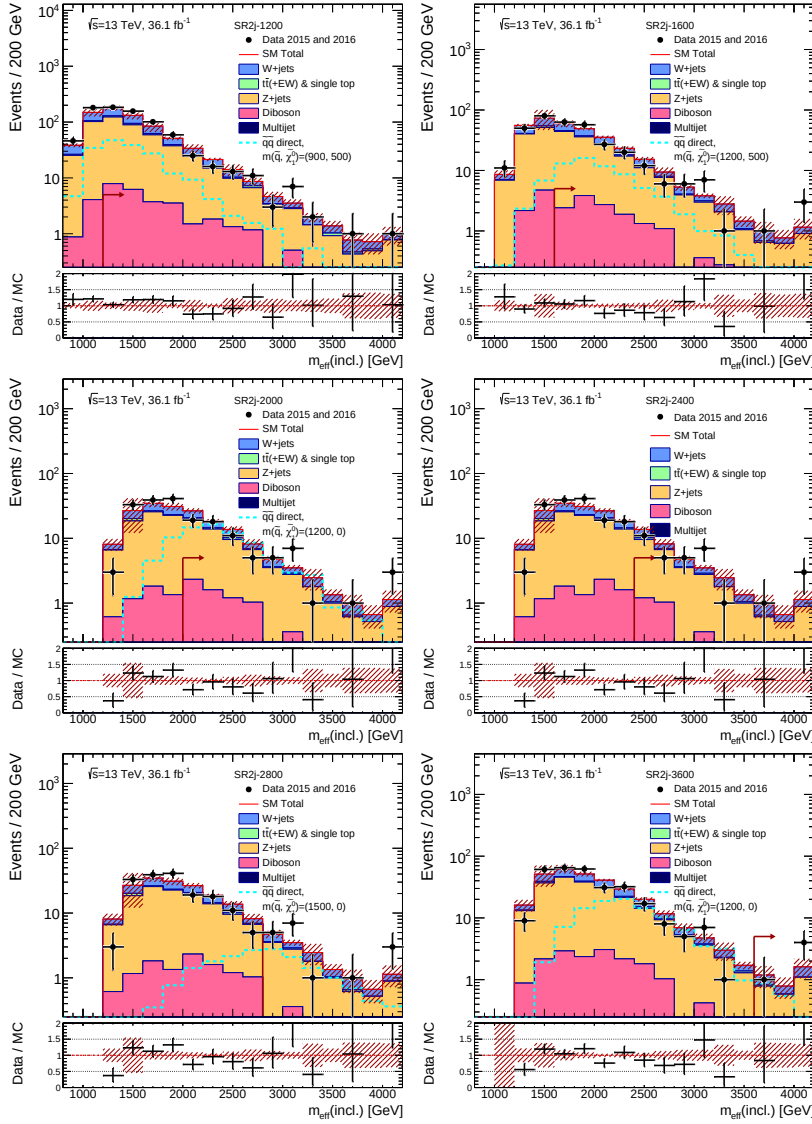


Figure 75: Observed  $m_{\text{eff}}(\text{inc})$  distributions in SR (**2j-1200** in Upper left, **2j-1600** in Upper right, **2j-2000** in Middle left, **2j-2400** in Middle right, **2j-2800** in Lower left and **2j-3600** in Lower right) with a loose  $m_{\text{eff}}$  cut. The histograms denote the MC background expectations, normalised to luminosity except for mutijet by jet smearing normalized in CRQ. Cross sections are the nominal one introduced in Section 7.9.1. The hatched error bands denote the combined experimental, MC statistical uncertainties.

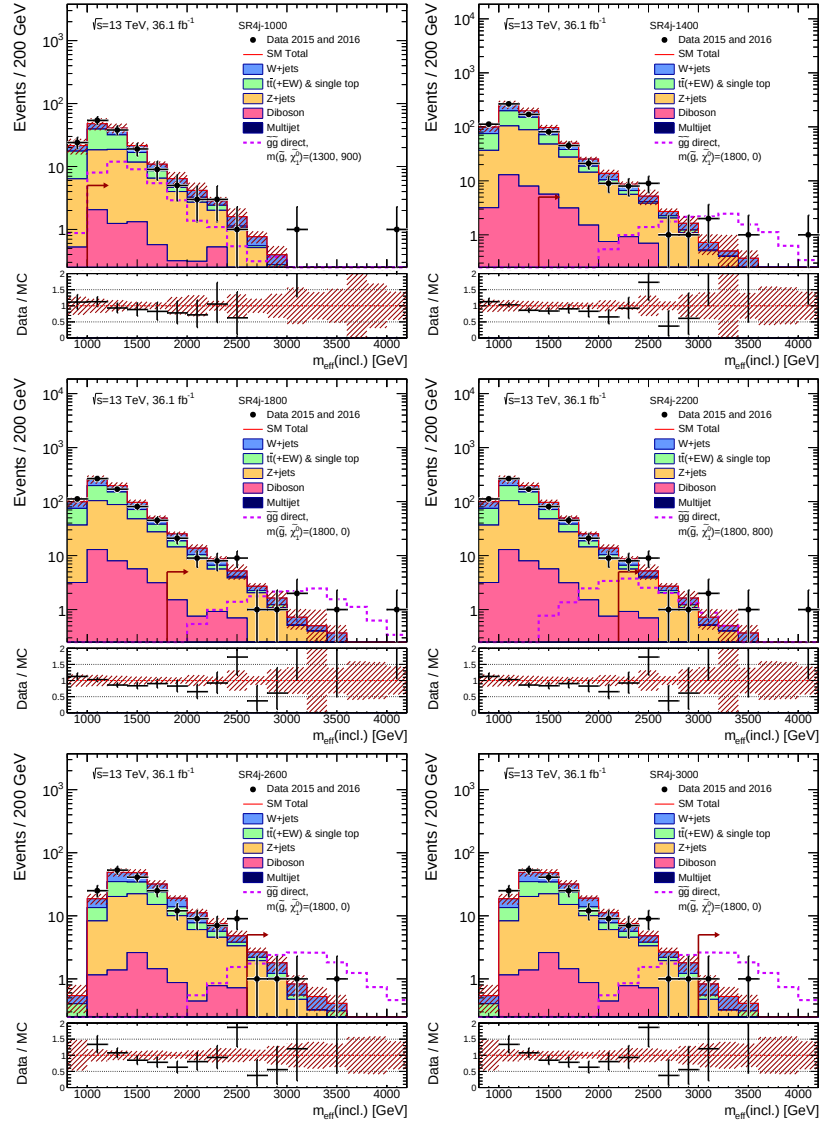


Figure 76: Observed  $m_{\text{eff}}(\text{inc})$  distributions in SR (**4j-1000** in Upper left, **4j-1400** in Upper right, **4j-1800** in Middle left, **4j-2200** in Middle right, **4j-2600** in Lower left and **4j-3000** in Lower right) with a loose  $m_{\text{eff}}$  cut. The histograms denote the MC background expectations, normalised to luminosity except for multijet by jet smearing normalized in CRQ. Cross sections are the nominal one introduced in Section 7.9.1. The hatched error bands denote the combined experimental, MC statistical uncertainties.

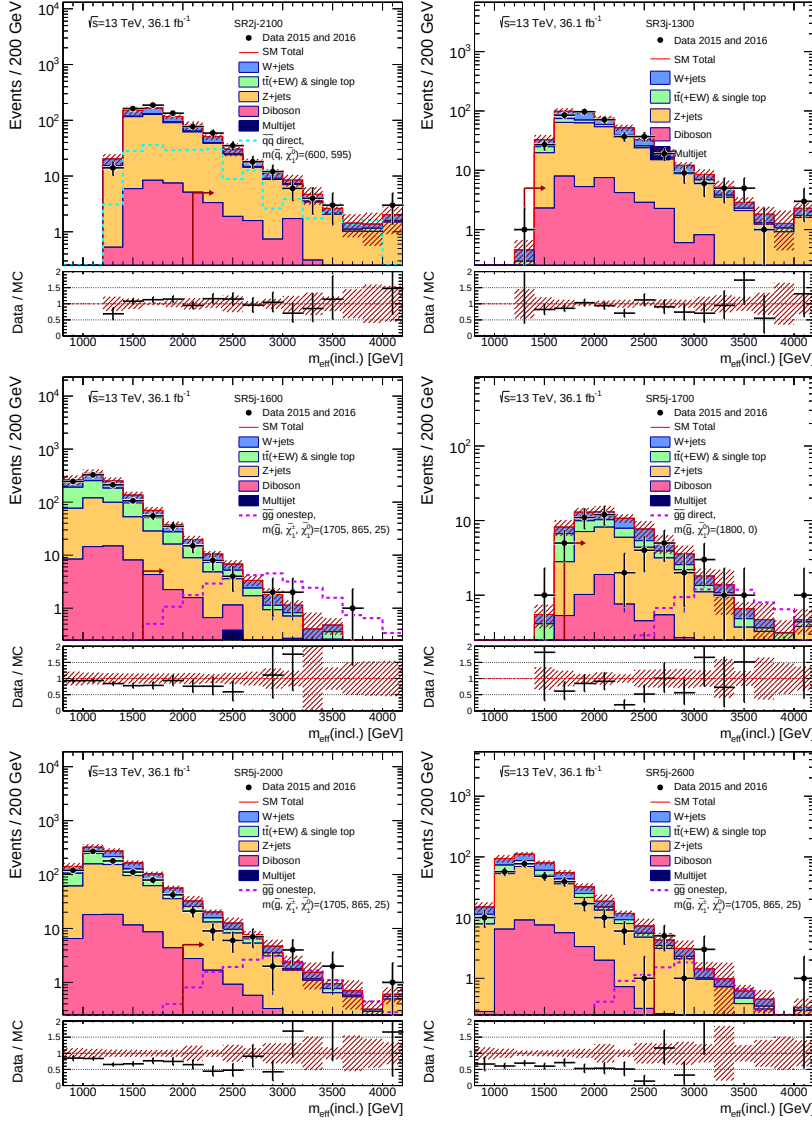


Figure 77: Observed  $m_{\text{eff}}(\text{inc})$  distributions in SR (**2j-2100** in Upper left, **3j-1300** in Upper right, **5j-1600** in Middle left, **5j-1700** in Middle right, **5j-2000** in Lower left, **5j-2600** in Lower right) with a loose  $m_{\text{eff}}$  cut. The histograms denote the MC background expectations, normalised to luminosity except for mutijet by jet smearing normalized in CRQ. Cross sections are the nominal one introduced in Section 7.9.1. The hatched error bands denote the combined experimental, MC statistical uncertainties.

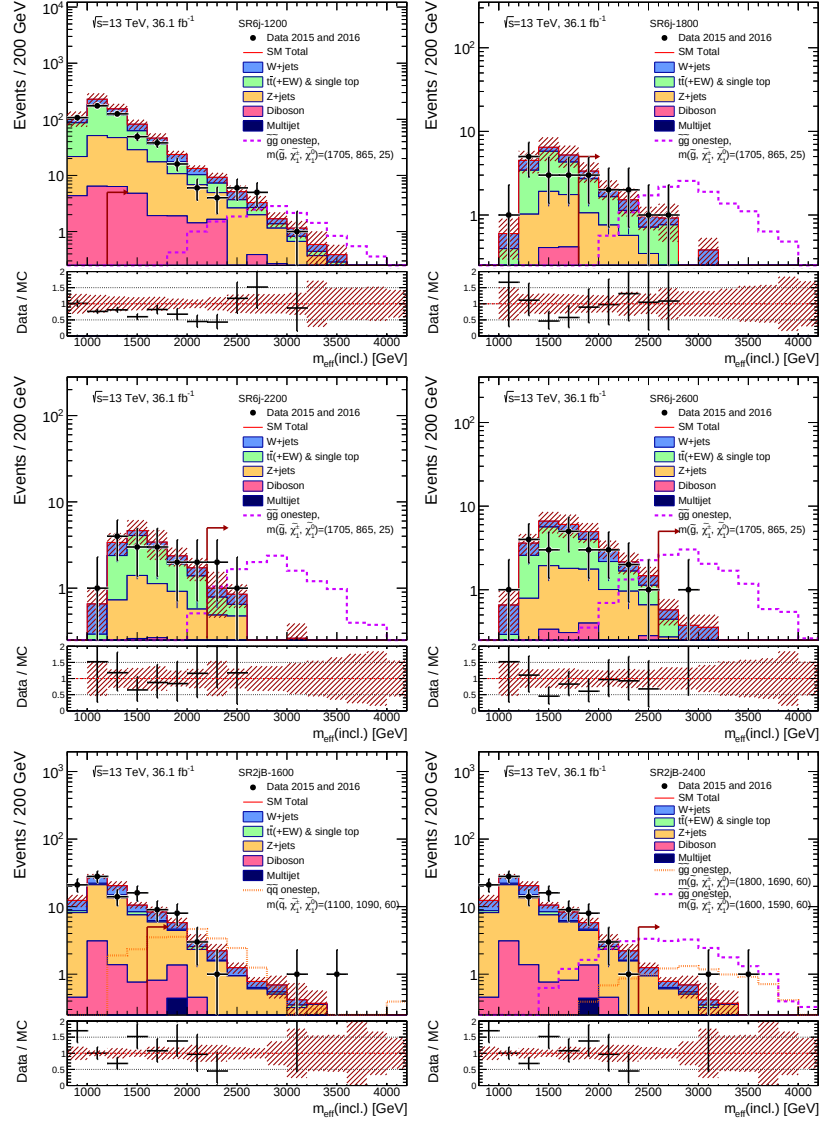


Figure 78: Observed  $m_{\text{eff}}(\text{inc})$  distributions in SR (**6j-1200** in Upper left, **6j-1800** in Upper right, **6j-2200** in Middle left, **6j-2600** in Middle right, **2jB-1600** in Lower left, **2jB-2400** in Lower right) with a loose  $m_{\text{eff}}$  cut. The histograms denote the MC background expectations, normalised to luminosity except for multijet by jet smearing normalized in CRQ. Cross sections are the nominal one introduced in Section 7.9.1. The hatched error bands denote the combined experimental, MC statistical uncertainties.

| Uncertainty of channel                        | SR 2jB-1600         |
|-----------------------------------------------|---------------------|
| Total background expectation                  | 20.60               |
| Total statistical ( $\sqrt{N_{\text{exp}}}$ ) | $\pm 4.54$          |
| Total background systematic                   | $\pm 3.62$ [17.57%] |
| Theory W+jets                                 | $\pm 2.50$ [12.2%]  |
| JER                                           | $\pm 1.09$ [5.3%]   |
| JES                                           | $\pm 1.05$ [5.1%]   |
| Theory Z/ $\gamma$ +jets                      | $\pm 1.3$ [6.3%]    |
| $\Delta\mu$ W+jets                            | $\pm 0.97$ [4.7%]   |
| $\Delta\mu$ Z+jets                            | $\pm 0.70$ [3.4%]   |
| Theory Diboson                                | $\pm 0.63$ [3.1%]   |
| pileUp                                        | $\pm 0.58$ [2.8%]   |
| JMR                                           | $\pm 0.55$ [2.7%]   |
| Theory Top                                    | $\pm 0.47$ [2.3%]   |
| JMS                                           | $\pm 0.37$ [1.8%]   |
| $\Delta\kappa$                                | $\pm 0.28$ [1.3%]   |
| MET                                           | $\pm 0.09$ [0.45%]  |
| $\Delta\mu$ Top                               | $\pm 0.05$ [0.26%]  |

Table 22: Breakdown of the dominant systematic uncertainties on background estimates in SR2jB-1600. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

VRs, especially in the dedicated validation regions **VR\*B**, defined in Section 7.9.6, where the nominal cuts on large-R jet masses are set as in the signal regions. Results in SR are in very good agreement with the SM predictions in **SR2jB-1600**. Differently, the background yield results to surmount the observed data in **SR2jB-2400**, which is due to the lack of statistics in that region.

Finally, the detailed systematic uncertainty summaries for the two SRs are shown in Table 22 and 23. In general, the looser selection in **SR2jB-1600** allows a lower statistical uncertainty and therefore a lower total uncertainty with respect to **SR2jB-2400**. The theoretical uncertainties on W+jets and Top background processes are considerably impacting on the results, given the similar topology of those processes to the signal model of reference. Moreover, the impact of the JMS and JMR uncertainties, whose values have been initially set as explained in Section 7.12, have been reduced after the fit, becoming not so relevant.

| Uncertainty of channel                        | SR 2jB-2400         |
|-----------------------------------------------|---------------------|
| Total background expectation                  | 3.89                |
| Total statistical ( $\sqrt{N_{\text{exp}}}$ ) | $\pm 1.97$          |
| Total background systematic                   | $\pm 0.98$ [25.21%] |
| Theory Top                                    | $\pm 0.57$ [14.7%]  |
| Theory W+jets                                 | $\pm 0.50$ [12.9%]  |
| Theory Z/ $\gamma$ +jets                      | $\pm 0.38$ [9.9%]   |
| $\Delta\mu$ Z+jets                            | $\pm 0.34$ [8.7%]   |
| $\Delta\mu$ W+jets                            | $\pm 0.19$ [5.0%]   |
| JMS                                           | $\pm 0.16$ [4.1%]   |
| JES                                           | $\pm 0.13$ [3.3%]   |
| JMR                                           | $\pm 0.12$ [3.0%]   |
| pileUp                                        | $\pm 0.07$ [1.8%]   |
| Theory Diboson                                | $\pm 0.06$ [1.6%]   |
| $\Delta\kappa$                                | $\pm 0.06$ [1.6%]   |
| MET                                           | $\pm 0.03$ [0.69%]  |
| JER                                           | $\pm 0.02$ [0.44%]  |
| $\Delta\mu$ Top                               | $\pm 0.02$ [0.40%]  |

Table 23: Breakdown of the dominant systematic uncertainties on background estimates in SR2jB-2400. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.



The background-only fit results have shown no significant excess over the standard model expectations in any of the signal regions. Therefore, the results can be used to set exclusion limits on the SUSY models introduced in Section 7.1, following the statistical method described in Section 6.6.2.

For some models, the results of the  $m_{\text{eff}}$ -based analysis presented in this work have been combined with a complementary search performed in the same final state with no leptons and jets and missing transverse momentum, which uses a different method of variable definition (RJR). A description of the RJR search can be found in [1]. The combination of the two searches, where present, proceeds such that the final observed and expected 95% CL exclusion limits are obtained from the signal regions belonging to the search providing with the best expected  $\text{CL}_s$  value.

## 8.1 UPDATED LIMITS ON SIMPLIFIED MODELS

### 8.1.1 Direct Decays

The limits at 95% confidence level (CL.) on two classes of simplified models with direct decays are shown in Figure 79, together with older limits set with  $3.2 \text{ fb}^{-1}$  [188]. The models consider only direct production of light-flavour mass-degenerate squarks or gluino pairs, as depicted in Figure 49. The limits are shown in terms of the two free parameter of the considered models, i.e  $m_{\tilde{g}/\tilde{q}}$  and  $m_{\tilde{\chi}_1^0}$ .

The upper limit of the excluded light-flavour squark mass region is 1.58 TeV assuming massless  $\tilde{\chi}_1^0$ . The corresponding limit on the gluino mass is 2.03 TeV, considering a massless  $\tilde{\chi}_1^0$ , resulting from the best excluding signal region **4j-3000**.

In the parameter region covering the "compressed" scenario with  $\Delta(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0}) \leq 50 \text{ GeV}$ , where the signal theory uncertainties described in Section 7.10.2 are more important on signal acceptance, masses of the squarks are excluded up to 650 GeV while the exclusion limits for the masses of the gluinos reach 1 TeV.

In general, the signal regions defined by the RJR search yield better exclusion limits for the squark grid, while those from the  $m_{\text{eff}}$ -based analysis perform better for gluino grids.

### 8.1.2 One-step Decays

In Figure 80, the resulting limits are shown for pair-produced light-flavour squarks or gluinos each decaying via an intermediate  $\tilde{\chi}_1^\pm$  to a

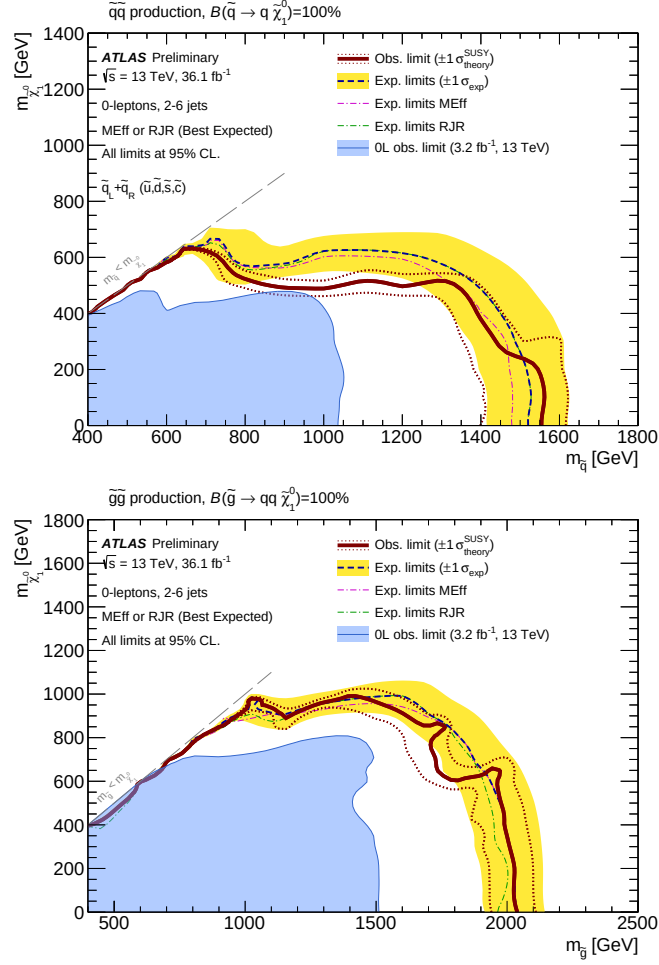


Figure 79: Exclusion limits for direct production of (top) light-flavour squark pairs with decoupled gluinos and (bottom) gluino pairs with decoupled squarks. Gluinos (light-flavour squarks) are required to decay to two quarks (one quark) and a LSP  $\tilde{\chi}_1^0$ . Expected limits from the MEff- and RJR-based searches separately are also shown for comparison. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.

quark (for squarks) or two quarks (for gluinos), a  $W$  boson and a  $\tilde{\chi}_1^0$ . The models are depicted in Figure 50. These models consider a mass spectra with fixed  $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{q}} + m_{\tilde{\chi}_1^0})/2$  (or  $(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$ ). The results are compared with the observed limits obtained by the previous ATLAS searches: [216] for squarks-pair production (top) and [188, 217] for gluinos pair-production (bottom).

In the models with squark-pair production,  $m_{\tilde{q}}$  up to 1.15 TeV are excluded for a massless  $\tilde{\chi}_1^0$ , while  $m_{\tilde{g}}$  are excluded up to 2.01 TeV with

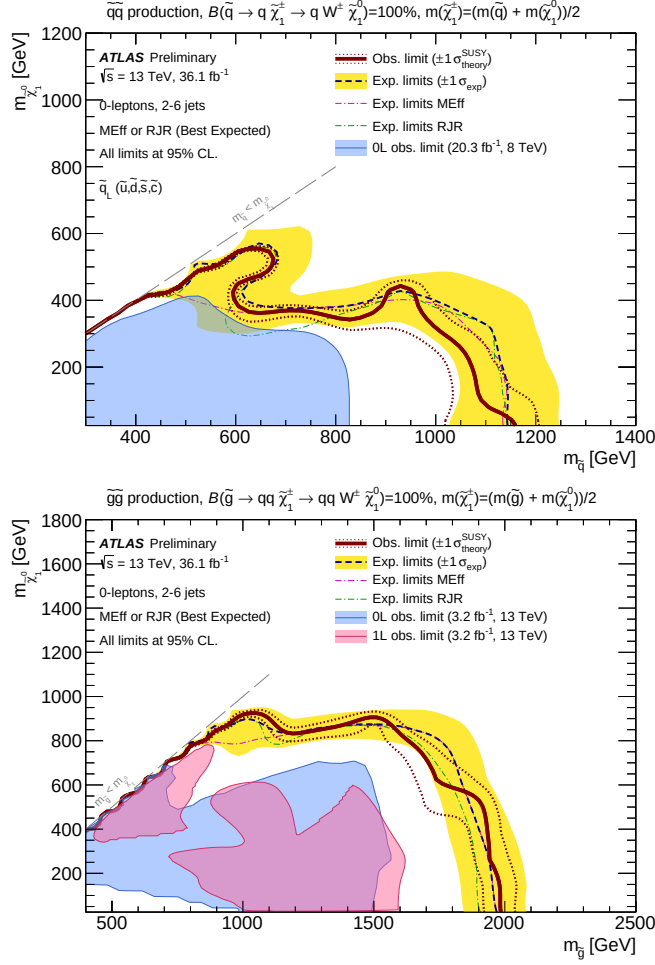


Figure 80: Exclusion limits for direct production of light-flavour  $\tilde{q}_L \tilde{q}_L$  pairs with decoupled gluinos (top) and  $\tilde{g}\tilde{g}$  pairs with decoupled squarks (bottom). Gluinos (light-flavour squarks) are required to decay to two quarks (one quark) and an intermediate  $\tilde{\chi}_1^\pm$ , to a  $W$  boson and a  $\tilde{\chi}_1^0$ . Neutralinos have fixed mass  $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{q}/\tilde{g}} + m_{\tilde{\chi}_1^0})/2$ . Expected limits from the  $m_{\text{eff}}$ - and RJR-based searches separately are also shown for comparison. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.

gluino-pair production. In the regions with very compressed spectra  $\Delta(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0}) \leq 50$  GeV, squark (gluino) masses are excluded up to 600 GeV (1 TeV). Exclusion limits on mass of the sparticles for models with intermediate decays are very similar to those obtained using models with direct decays.

## 8.2 LIMITS SET WITH BOOSTED ANALYSIS

The Boosted signal regions **2jB** have been designed to expand the sensitivity for simplified models with intermediate decays to  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  subsequently decaying to W,Z bosons and  $\tilde{\chi}_1^0$ , as depicted in Figure 50 and 51, in the mass spectra where  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  are close to degenerate in mass with the sparticle parents (squarks/gluinos).

The limits for the models containing a W boson and with fixed  $m_{\tilde{\chi}_1^0} = 60$  GeV are presented in Figure 81. In the figure, the best performing signal region in terms of  $\text{CL}_s$  exclusion is displayed for each of the signal points considered in the  $(\chi, m_{\tilde{g}/\tilde{q}})$  parameter space, where  $\chi$  is the boost parameter defined by Eq. (99). The results are compared with the observed limits obtained by the previous ATLAS searches: [216] for squarks-pair production (top) and [188, 217] for gluinos pair-production (bottom).

Taking advantage of their unique requirements designed to tag hadronic decays of the W bosons, the **2jB** signal regions are best performing for both models in the boosted area, where their sensitivity far surpasses the other SRs of both the  $m_{\text{eff}}$ - and RJR-based analyses. A direct evaluation of the effect of the boosted signal regions on the analysis exclusion power can be done by comparing the limits in Figure 81 with their counterparts in Figure 82 provided by the ATLAS search in events with an isolated lepton, jets, and  $E_T^{\text{miss}}$  (1-lepton) performed on the same dataset of  $36.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$  [218]. As it can be noticed, the mass range excluded by the 1-lepton analysis is comparable in the non-boosted area while it becomes much lower when approaching to  $\chi \sim 1$ .

It is also remarkable to note that the **5j-2600** signal region results often to be the best performing one in the "intermediate boosted" region, where  $\chi \sim 0.8$ , confirming the purpose of its optimisation as described in Section 7.8.1.

The limits for gluino-pair production decaying via an intermediate  $\tilde{\chi}_2^0$  to two quarks, a Z boson and a  $\tilde{\chi}_1^0$ , with the mass of the  $\tilde{\chi}_1^0$  set to 1 GeV, are shown in Figure 83. In these models, gluino masses below 2.0 TeV are excluded for  $m_{\tilde{\chi}_2^0} \sim 1 \text{ TeV}$ , as obtained from the signal region **4j-3000**. As expected, the **2jB** signal regions are better performing in the compressed scenario where  $m_{\tilde{g}} \sim m_{\tilde{\chi}_2^0}$  and sufficient boost is provided to the Z boson.

## 8.3 LIMITS ON NEW MODELS FOR 0-LEPTON ANALYSIS

The 0-lepton analysis on the 2015+2016 Run2 data implemented also the limits on new signal models with mixed decays of intermediate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  for squark-pair and gluino-pair production as illustrated in the diagrams in Figure 52. The mass spectra follows the same strategy as the models above, with fixed  $m_{\tilde{\chi}_1^0} = 60 \text{ GeV}$ . Sensitivity studies have been conducted in order to test a similar approach using large-R jets for tagging boosted W/Z/h bosons, but no significative gain in the analysis

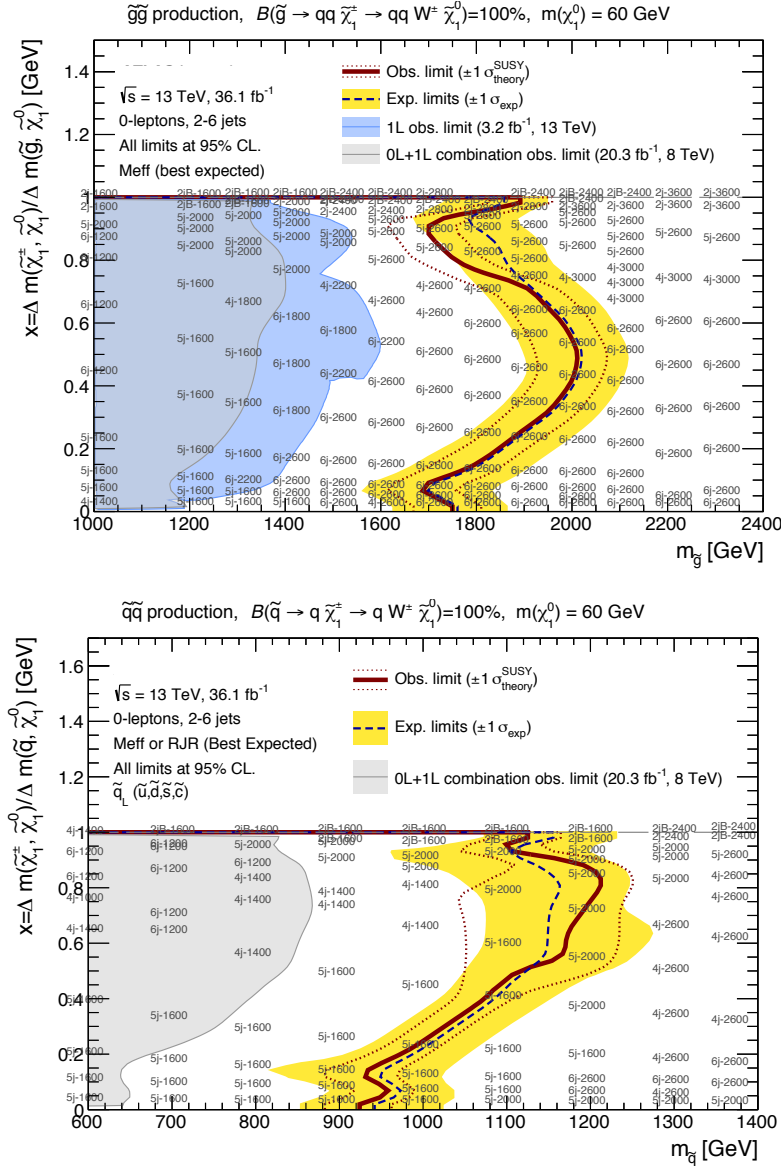


Figure 81: Exclusion limits for direct production of light-flavour  $\tilde{q}_L \tilde{q}_L$  pairs with decoupled gluinos (top) and  $\tilde{g}\tilde{g}$ -pairs with decoupled squarks (bottom). Gluinos (light-flavour squarks) are required to decay to two quarks (one quark) and an intermediate  $\tilde{\chi}_1^\pm$ , decaying to a  $W$  boson and a  $\tilde{\chi}_1^0$ . Models have a fixed  $m_{\tilde{\chi}_1^0} = 60$  GeV and varying values of  $m_{\tilde{g}}$  (or  $m_{\tilde{q}}$ ) and  $m_{\tilde{\chi}_1^\pm}$  are considered. Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.

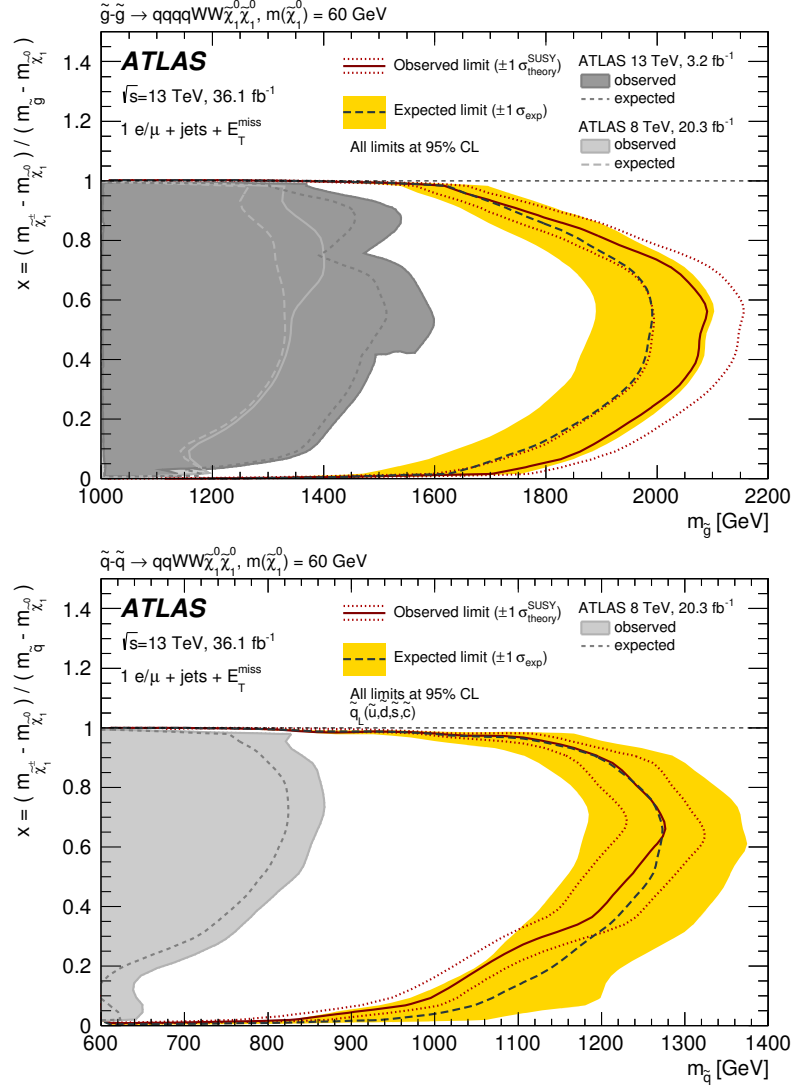


Figure 82: Exclusion contours set by 1-lepton analysis [218] for direct production of light-flavour  $\tilde{q}_L\tilde{q}_L$  pairs with decoupled gluinos (top) and  $\tilde{g}\tilde{g}$ -pairs with decoupled squarks (bottom). Gluinos (light-flavour squarks) are required to decay to two quarks (one quark) and an intermediate  $\tilde{\chi}_1^\pm$ , decaying to a  $W$  boson and a  $\tilde{\chi}_1^0$ . Models have a fixed  $m_{\tilde{\chi}_1^0} = 60$  GeV and varying values of  $m_{\tilde{g}}$  (or  $m_{\tilde{q}}$ ) and  $m_{\tilde{\chi}_1^\pm}$  are considered. The Figures are taken from [218].

sensitivity has been observed. Nevertheless, the interpretation using the analysis signal regions has been conducted, whose results are shown in Figure 84. The results don't cover the region up to  $x \approx 1$  because no signal points for this model have been generated for those values of the parameter space.

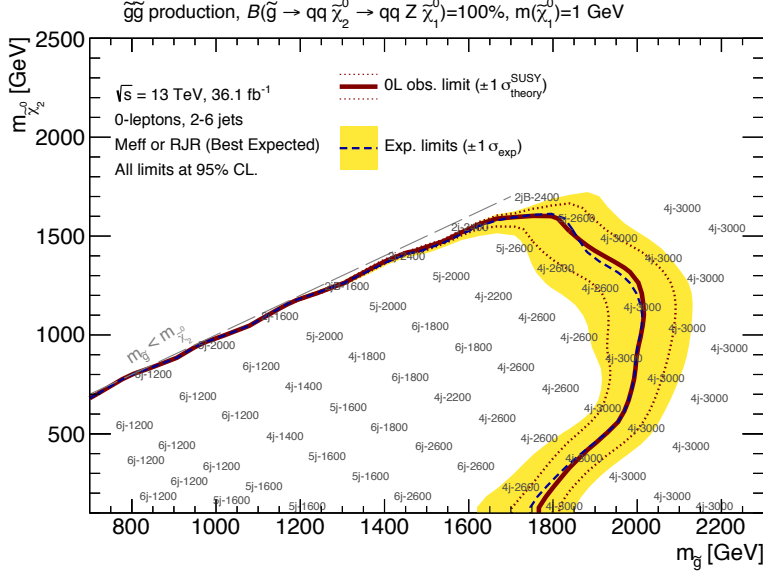


Figure 83: Exclusion limits for pair-produced gluinos each decaying via an intermediate  $\tilde{\chi}_2^0$  to two quarks, a Z boson and a  $\tilde{\chi}_1^0$  for models with a fixed  $m_{\tilde{\chi}_1^0} = 1$  GeV and varying values of  $m_{\tilde{g}}$  and  $m_{\tilde{\chi}_2^0}$ . Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.

#### 8.4 LIMITS ON PHENOMENOLOGICAL MSSM MODEL

An additional interpretation of the analysis results has been made in the context of simplified phenomenological MSSM models assuming only gluinos, light-flavour squarks and neutralinos ( $\tilde{\chi}_1^0$ ). The latter is assumed to be *purely bino*, as described in the theory introduction in Section 2.4.3. The models vary the squark and gluino masses, while the mass of neutralino is set to be  $m_{\tilde{\chi}_1^0} = 0, 695, 995$  GeV. The limits are shown in the  $(m_{\tilde{g}}, m_{\tilde{q}})$  plane in Figure 85. In the scenario with massless  $\tilde{\chi}_1^0$ , gluino masses up to  $\sim 2$  TeV are excluded (top) for high squark masses, which is a consistent result compared to what found using simplified models of gluino-pair production with decoupled squark masses. On the contrary, a much higher limit of  $\sim 2.2$  TeV (for  $m_{\tilde{g}} \sim 6$  TeV) on the squark mass is found, compared to the results using the simplified model with squark-pair production, due to the larger cross section present in the squark-pair production case via gluino exchange diagrams. For increasing values of  $m_{\tilde{\chi}_1^0}$  the exclusion reach tends to become worse.

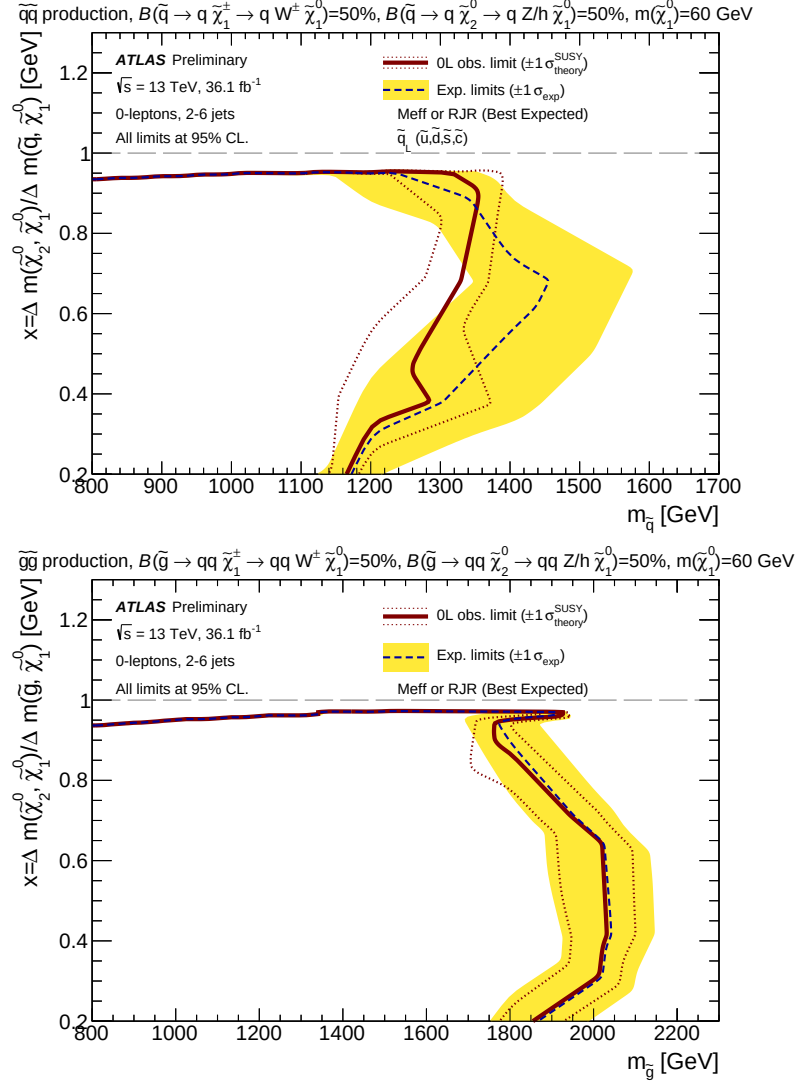


Figure 84: Exclusion limits for direct production of (top) light-flavour squark<sub>L</sub> pairs with decoupled gluinos and (bottom) gluino pairs with decoupled squarks. Gluinos (light-flavour squarks) are required to decay to two quarks (one quark) and a intermediate  $\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0$  at 50% BR, respectively.  $\tilde{\chi}_1^\pm$  decays to a  $W$  boson and a  $\tilde{\chi}_1^0$ , and  $\tilde{\chi}_2^0$  decays to a  $Z$  or a  $h$  boson and  $\tilde{\chi}_1^0$ . Models with a fixed  $m_{\tilde{\chi}_1^0} = 60$  GeV are considered varying  $m_{\tilde{g}}$  (or  $m_{\tilde{q}}$ ) and  $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0}$ . Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties.



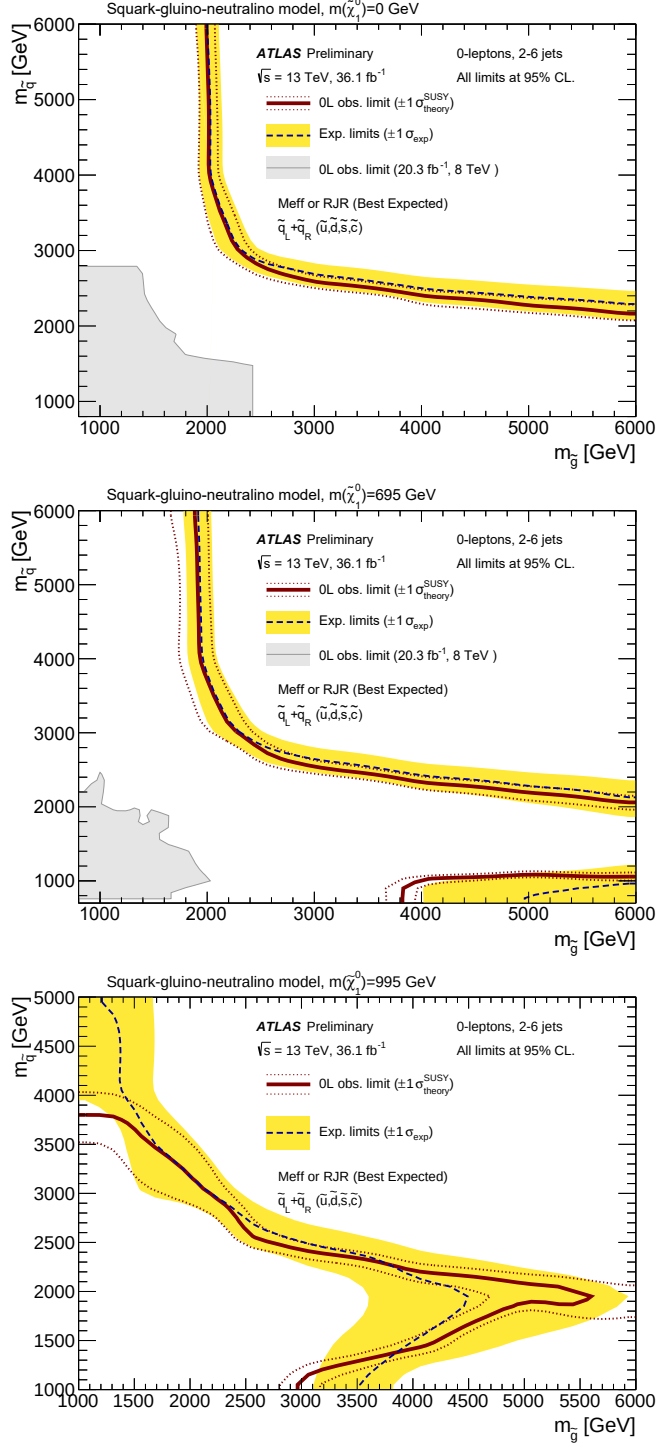


Figure 85: Exclusion limits for inclusive squark-gluino productions in pMSSM models with  $m_{\tilde{\chi}_1^0} = 0$  GeV (top),  $m_{\tilde{\chi}_1^0} = 695$  GeV (center) and  $m_{\tilde{\chi}_1^0} = 995$  GeV (bottom), varying values of  $m_{\tilde{g}}$  and  $m_{\tilde{q}}$  assuming purely bino  $\tilde{\chi}_1^0$ . Exclusion limits are obtained by using the signal region with the best expected sensitivity at each point. The blue dashed lines show the expected limits at 95% CL, with the light (yellow) bands indicating the  $1\sigma$  excursions due to experimental and background-only theoretical uncertainties. Observed limits are indicated by medium dark (maroon) curves where the solid contour represents the nominal limit, and the dotted lines are obtained by varying the signal cross section by the renormalization and factorization scale and PDF uncertainties. Results (top, center) are compared with the observed limits obtained by the Run1 0-lepton ATLAS search [3].



## CONCLUSIONS

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Supersymmetry, introduced in Chapter 2, is one of the most favourable theories for physics beyond the SM and has been investigated by a large fraction of the LHC physics program since the start of the accelerator in 2009 in the two data-taking periods ultimated at the time of the preparation of this thesis, the Run1 in 2011-2012 at  $\sqrt{s} = 7\text{-}8$  TeV and the Run2 in 2015-2016 at  $\sqrt{s} = 13$  TeV.

### 9.1 ANALYSIS SUMMARY

In this thesis, a search for squarks and gluinos in final states with jets and  $E_{\text{T}}^{\text{miss}}$  using  $36.1 \text{ fb}^{-1}$  of the Run2 dataset at  $\sqrt{s} = 13$  TeV collected with the ATLAS detector was presented. The 0-lepton analysis covers a wide range of the mass spectrum of the SUSY strongly produced particles with its 24 inclusive signal regions optimised on several different SUSY simplified models. The boosted analysis, with its two dedicated signal regions optimised upon the introduction of a new jet reconstruction algorithm, the jet *reclustering* (Section 5.3), contributes to enlarge the exclusion reach of the  $m_{\text{eff}}$ -based analysis in a specific parameter space, where bosons have sufficient boost to be reconstructed within a single large-R jet, as described in Section 7.8.

The analysis results, presented in Section 7.13, show no hints for the existence of squarks or gluinos and a general good agreement with the expectations from the SM is found. The interpretations using different SUSY models allow to set exclusion limits on the mass of the SUSY particles up to 2.03 TeV for the gluinos (assuming a massless  $\tilde{\chi}_1^0$ ) and up to 1.58 TeV for strong production of squarks of the first and second generations. Other limits set on different models, including those using the boosted signal regions, are shown in Sections 8.2, 8.3 and 8.4. These results broadly extend the region of the SUSY parameter space already investigated by previous LHC searches and set new limits for models not previously investigated.

### 9.2 DISCUSSION

The 0-lepton analysis, given its final state, is one of the most inclusive and powerful searches among the ATLAS physics program for the research of SUSY particles. Moreover, the analysis is optimised on models concerning SUSY strong production, which is the most favoured production mode in terms of cross-section to appear in the early Run2 data taking, as shown in Figure 6. Furthermore, the expected total integrated luminosity to be delivered by the LHC at the end of Run3 (end of 2023) is  $\sim 300 \text{ fb}^{-1}$ , which is not likely to add a decisive impact to the spar-

ticles mass reach that may be accessible. All this means that the room for discovery of SUSY particles within the dataset collected by ATLAS detector from  $pp$  collisions at LHC is getting tighter and tighter.

The indisputable lack of any sign of new physics in the SUSY sector, and truthfully in any search for physics beyond SM, requires some thought in order to understand the reasons why SUSY has not been discovered yet and whether the tremendous effort involved so far in the SUSY search program is supposed to continue or needs to be redetermined.

There can be several reasons why squarks and gluinos have not appeared yet in events with jets and  $E_T^{\text{miss}}$ . Supersymmetry has been searched for under a set of assumptions that may not necessarily be true. Possible reasons for the non-observation of any existing SUSY particles include:

- $\tilde{q}/\tilde{g}$  are still too heavy** The analyses might be simply not sensitive to the SUSY spectrum if sparticles have masses out of the reach of the LHC. Some arguments in favor of the mass values to not be exceeding larger than 1 TeV are discussed in Section 2.4. However there is no conclusive argument on this topic.
- Compressed spectra** The events from the parameter space where the difference between the masses of the squark/gluino and the  $\tilde{\chi}_1^0$  is very small (within 10 GeV) have soft jets and possibly low- $E_T^{\text{miss}}$ , given the absence of high-energy objects the  $E_T^{\text{miss}}$  can recoil from. These kind of events are more difficult to be separated from SM background and may be probed solely through ISR and FSR (mostly in analysis with mono-jet signatures).
- Heavy LSPs** The analysis is optimised for high values of squark/gluino masses, therefore is not very sensitive to scenarios with high  $\tilde{\chi}_1^0$  masses.
- Different decays** Longer cascade decays may result in jets that are too soft to pass the selection cuts, or may include leptons in the final state that are vetoed by the 0-lepton analysis. ATLAS research program includes also searches using leptons, with no hints for SUSY so far [218, 219]. On the other hand, the 0-lepton analysis considers only prompt decays of the sparticles, which instead may decay with longer lifetimes and therefore be out of its sensitivity. This scenario is investigated by different dedicated searches with no hints for SUSY so far too [220, 221].

Particularly referring to the first point, other SUSY particles than  $\tilde{q}/\tilde{g}$  could be lighter and might be discovered first. The searches for charginos, neutralinos, and sleptons result generally in lower limits due to their lower cross section. Direct electroweak productions of charginos and sleptons are therefore favored in the continuation of the physics research with the ATLAS detector in the last data-taking period of the Run2 (2017-2018) and in the following Run3, to be started in 2021.

### 9.3 OUTLOOK

Despite the lack of hints for new physics found so far, there are still strong motivations for SUSY to be investigated, e.g. its feature to solve the hierarchy problem reducing the large virtual corrections to the mass of the Higgs boson, which introduces a certain degree of un-naturalness in the SM.

The 0-lepton channel continues to be an interesting signature and be sensitive to many models containing not too heavy squarks and gluinos. Although no large improvements can be achieved by the increase of the integrated luminosity in the current run of the LHC, there are several improvements on the analysis that might help in broadening its sensitivity and reducing the systematic uncertainties, in order to achieve discovery or improve further exclusion limits.

Several remarks can be made by comparing the ATLAS results with those obtained by the CMS collaboration in the analyses targetting squarks and gluinos [222]. A different categorization of the signal regions in a bigger number of orthogonal bins is used. Subsequently, a simultaneous fit in all these bins (*multi-bin* fit) is performed, which seems to provide a similar exclusion power on the squark and gluino masses but a higher one on the  $\tilde{\chi}_1^0$  mass, which is excluded by 200 GeV better than the ATLAS result.

On an other note, the use of multivariate discriminator output, e.g. from Boosted Decision Tree (BDT), brings a more sophisticated approach to the signal region definition and may lead to an increase of the analysis sensitivity.

Finally, the boosted analysis may benefit of a deeper study on different boson tagging methods based on the jet substructure properties, which is a field of increasing interests within the ATLAS community.

All of the described research lines are currently under investigation within the ATLAS 0-lepton working group in connection with the corresponding combined performance groups. The interest in searching for SUSY particles is therefore not ceased. SUSY stays as a pillar of the ATLAS physics program, which benefits of the outstanding performances of the ATLAS detector in collecting and delivering high quality data.



Part IV

APPENDIX





## CONTROL REGION PLOTS FOR BOOSTED ANALYSIS

In this Appendix are shown the distributions of the main discriminant variables used to define the **2jB** signal regions for the Boosted analysis, in their corresponding control regions. The CRs are defined in Section 7.9.6.

### A.1 CONTROL REGION PLOTS FOR 2JB-1600

Figures 86-94 show the distributions in CRs corresponding to **2jB-1600**.

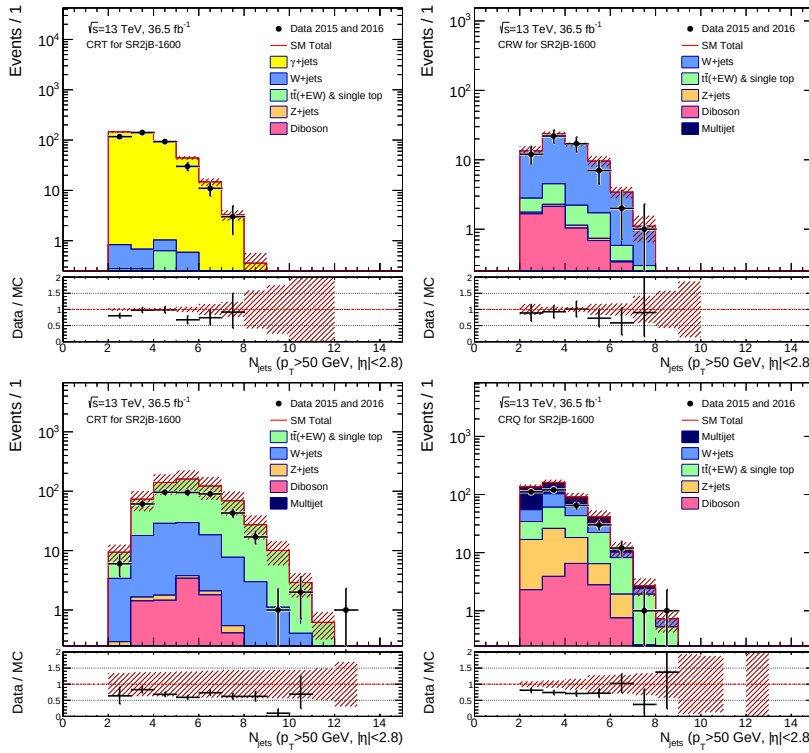


Figure 86: Observed  $N_{\text{jets}}$  distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

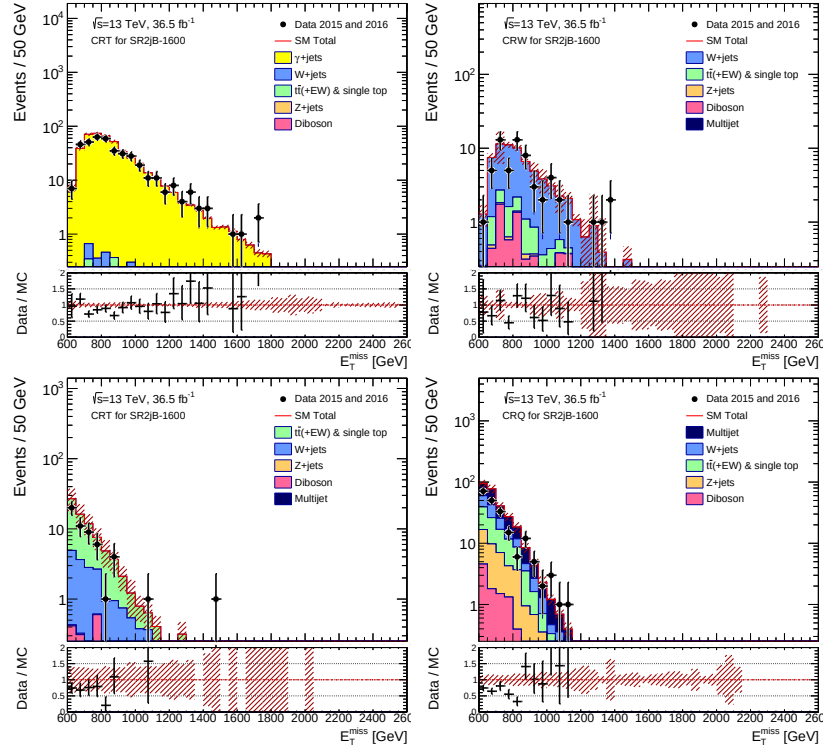


Figure 87: Observed missing transverse energy distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

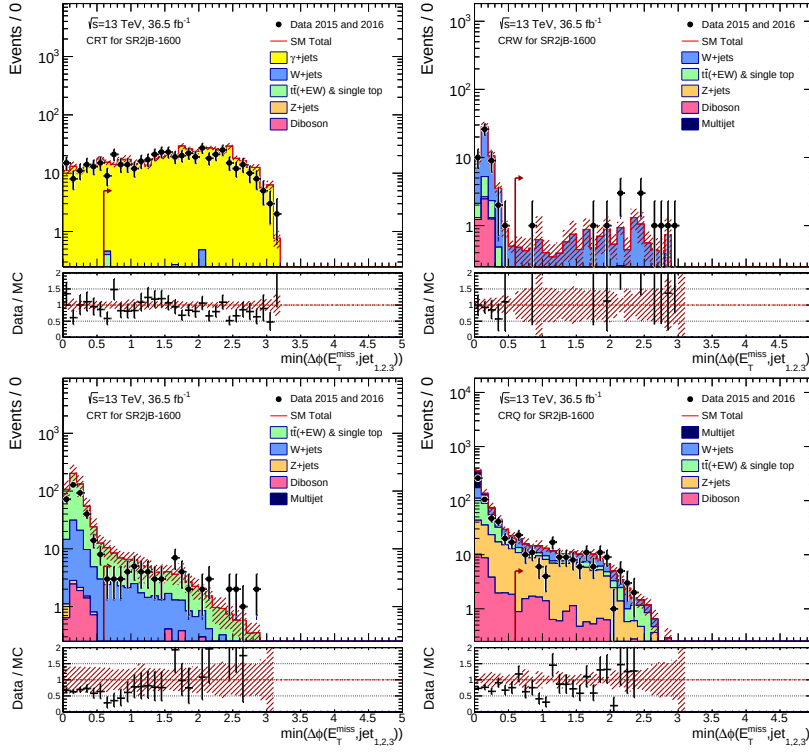


Figure 88: Observed  $\Delta\phi$  distributions in **2JB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

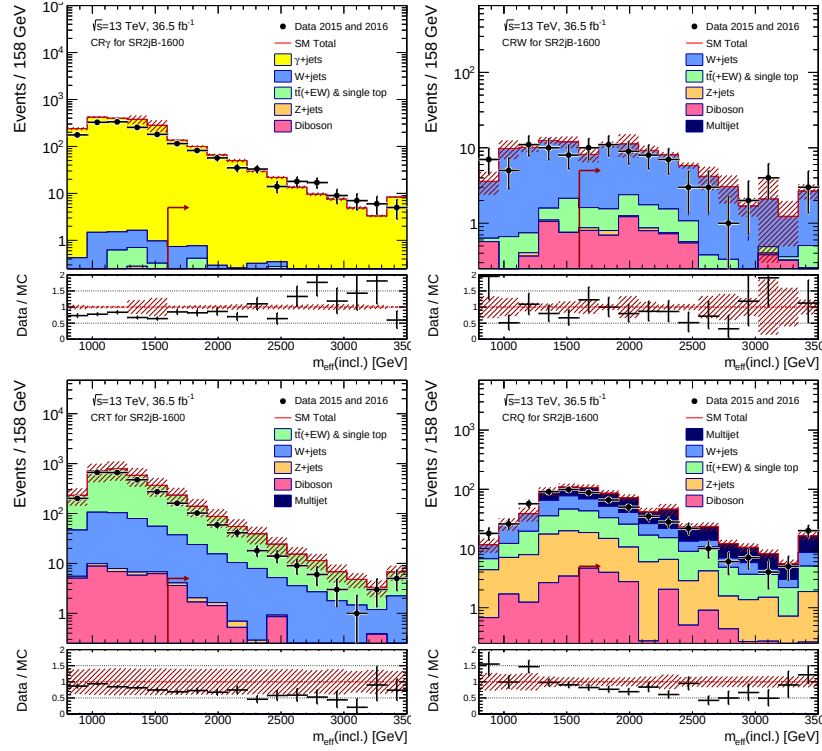


Figure 89: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

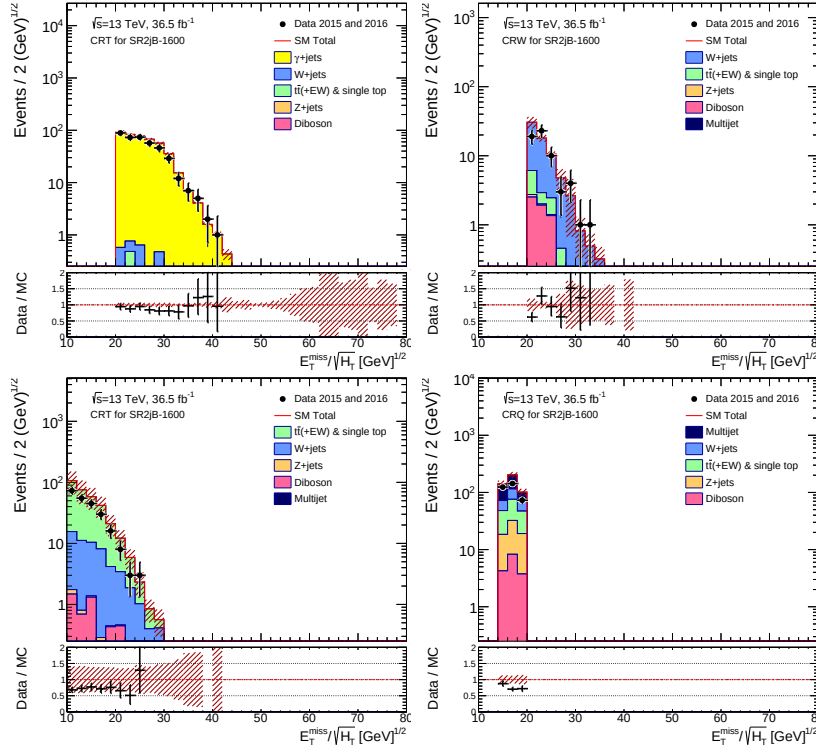


Figure 90: Observed  $E_T^{\text{miss}}/\sqrt{H_T}$  distributions in **2JB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

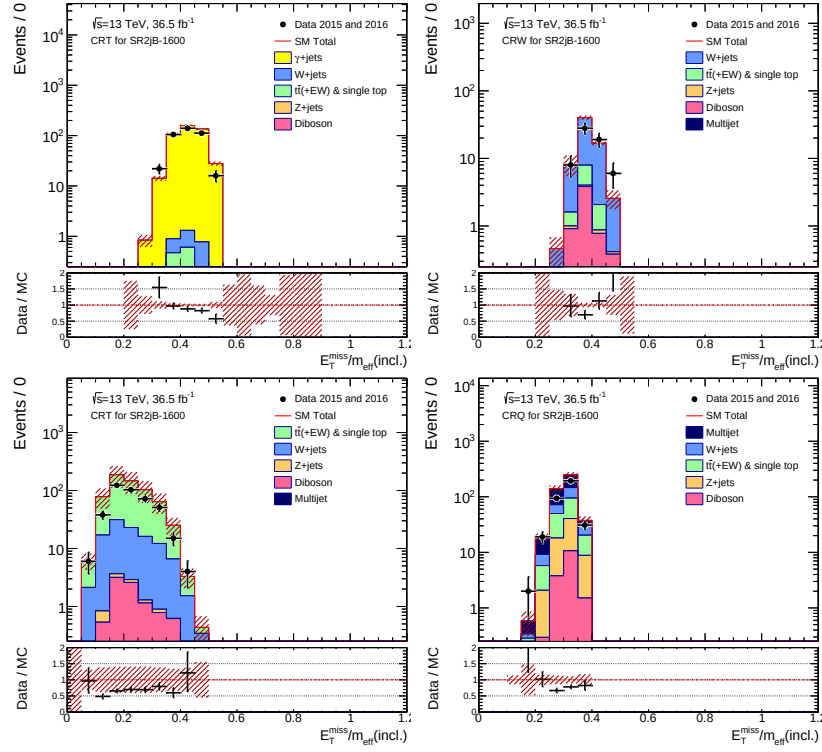


Figure 91: Observed  $E_T^{\text{miss}}/m_{\text{eff}}(2j)$  distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

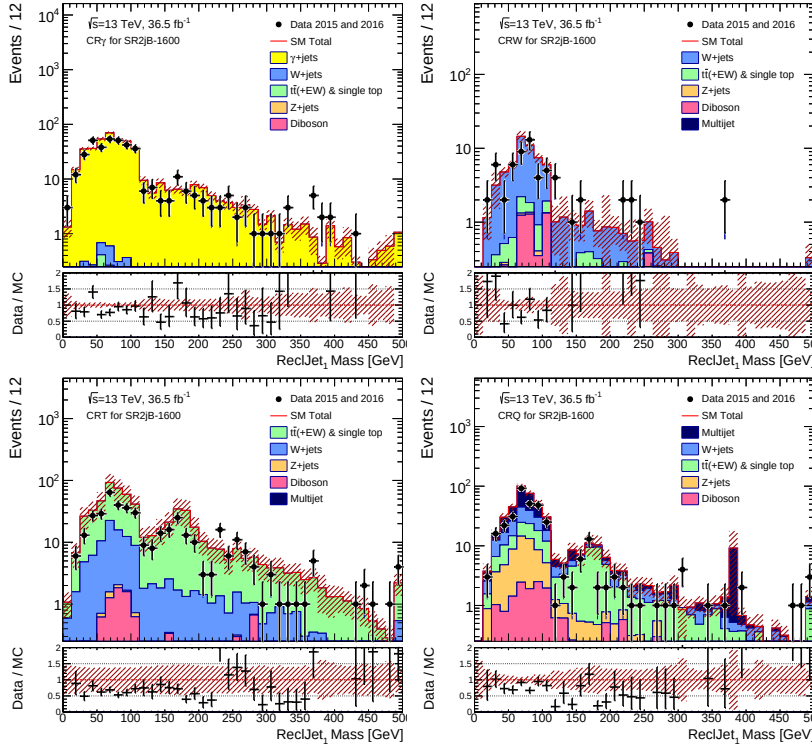


Figure 92: Observed  $m(R_{j1})$  distributions in **2JB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

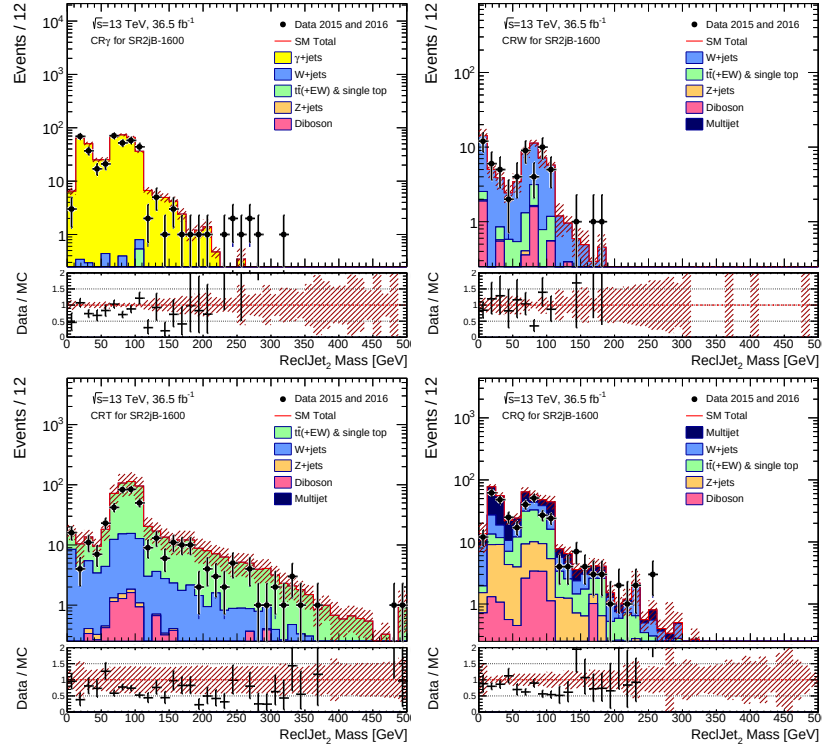


Figure 93: Observed  $m(R_{j2})$  distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.



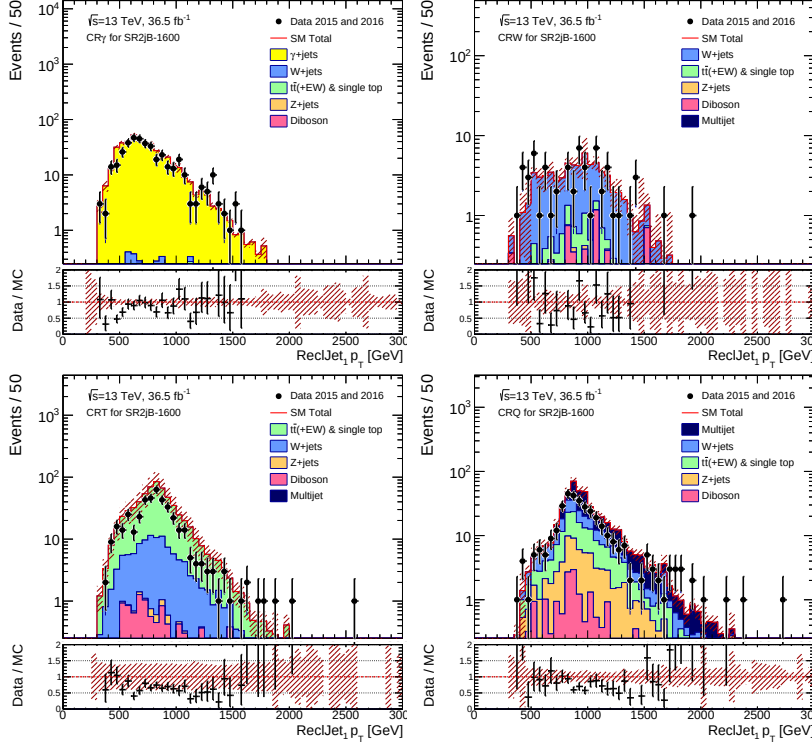


Figure 94: Observed  $p_T(Rj_1)$  distributions in **2JB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

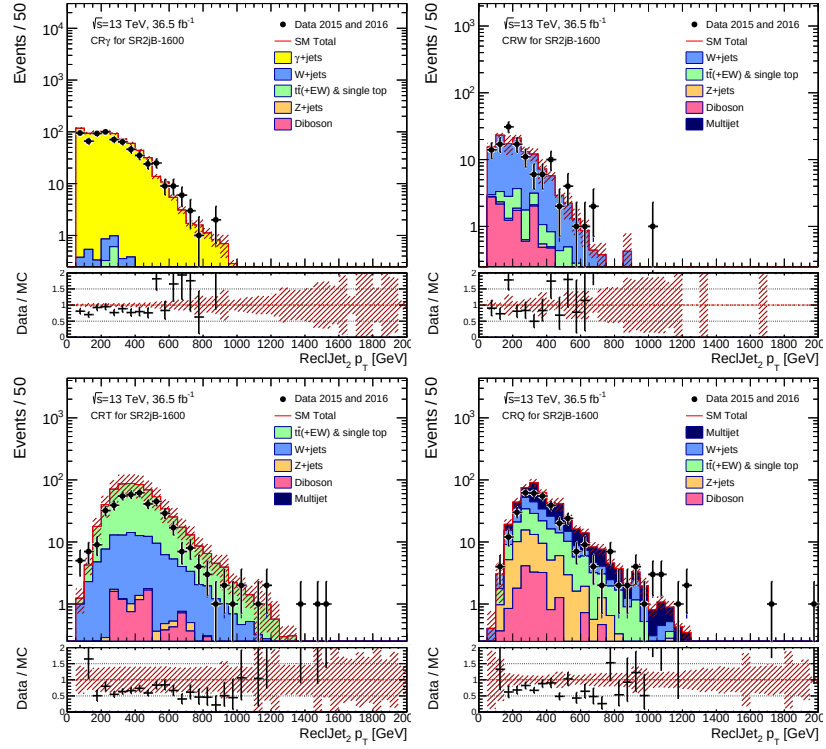


Figure 95: Observed  $p_T(R_{j1})$  distributions in **2jB-1600** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

## A.2 CONTROL REGION PLOTS FOR 2JB-2400

Figures 96-104 show the distributions in CRs corresponding to **2jB-2400**.

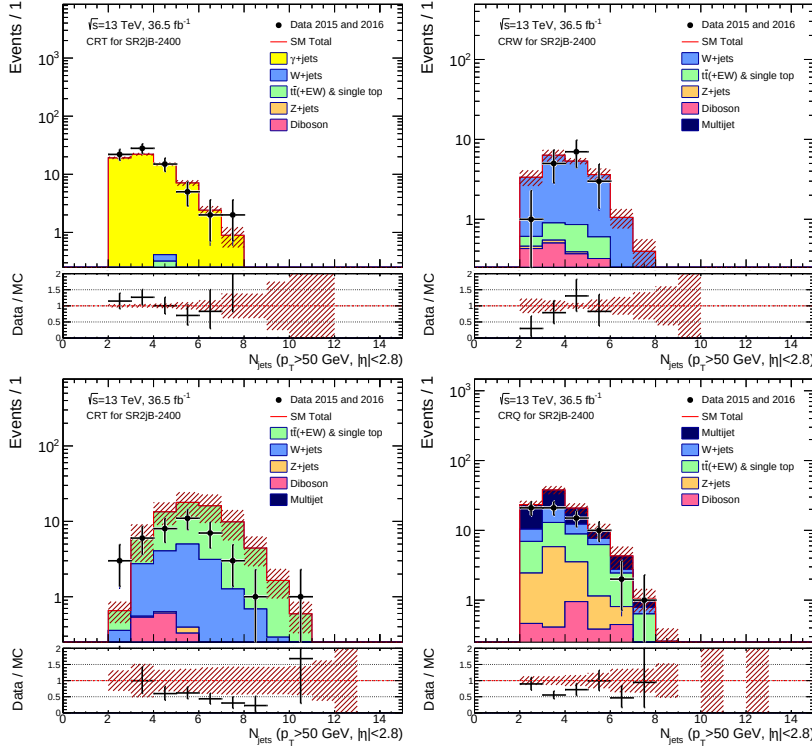


Figure 96: Observed  $N_{\text{jets}}$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

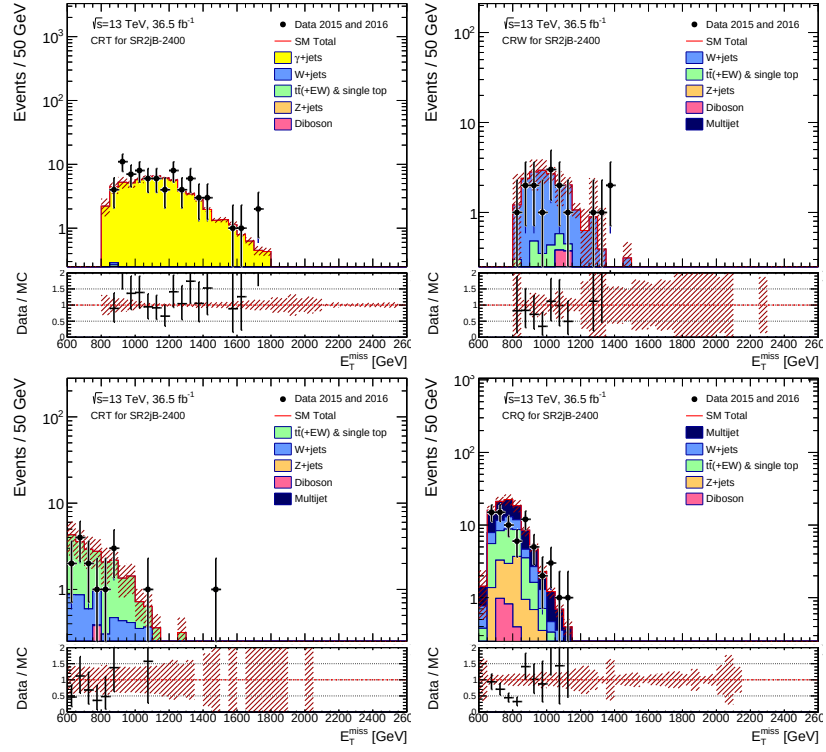


Figure 97: Observed missing transverse energy distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

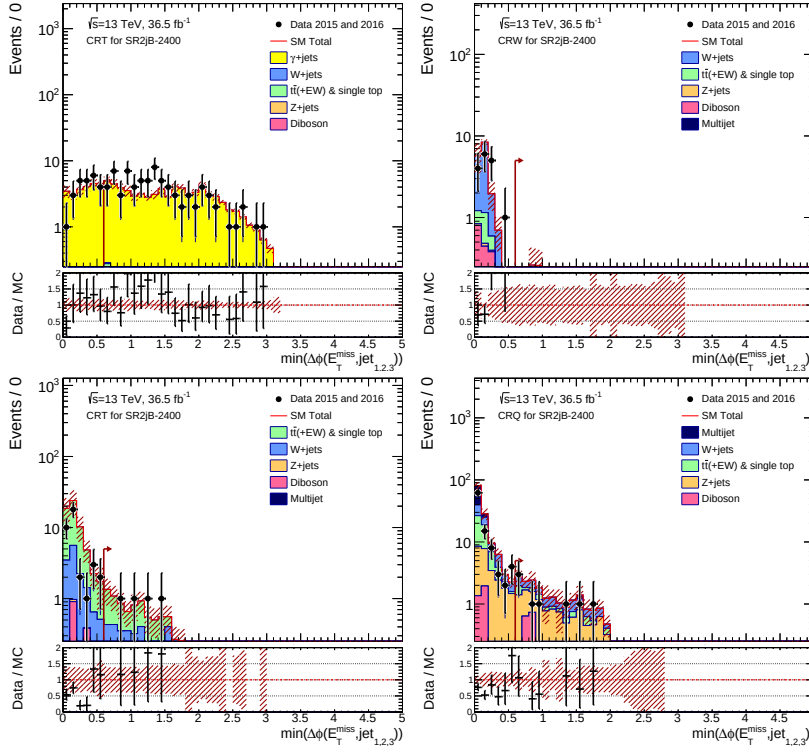


Figure 98: Observed  $\Delta\phi$  distributions in **2JB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

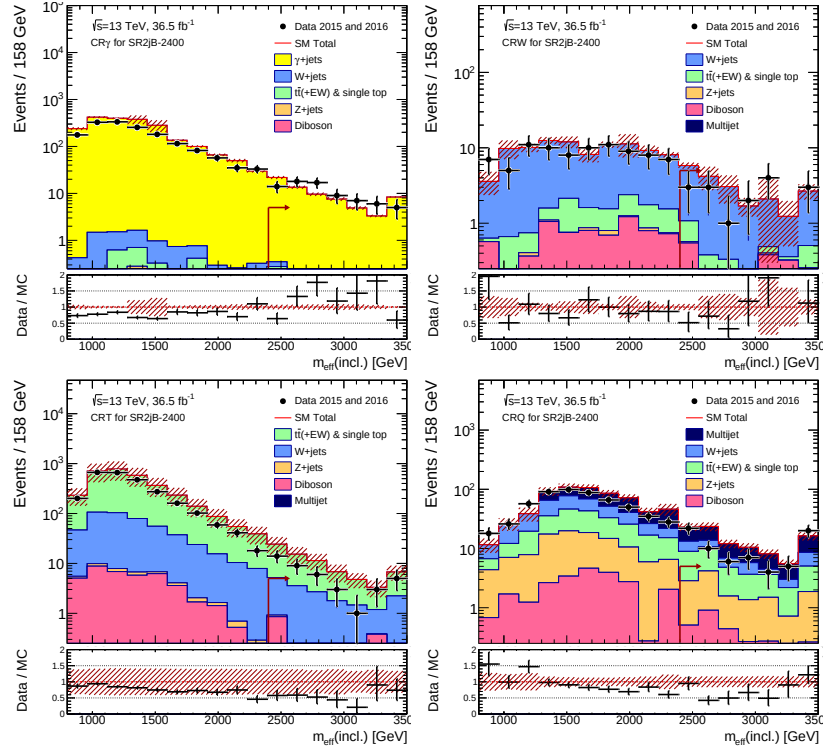


Figure 99: Observed  $m_{\text{eff}}(\text{incl.})$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

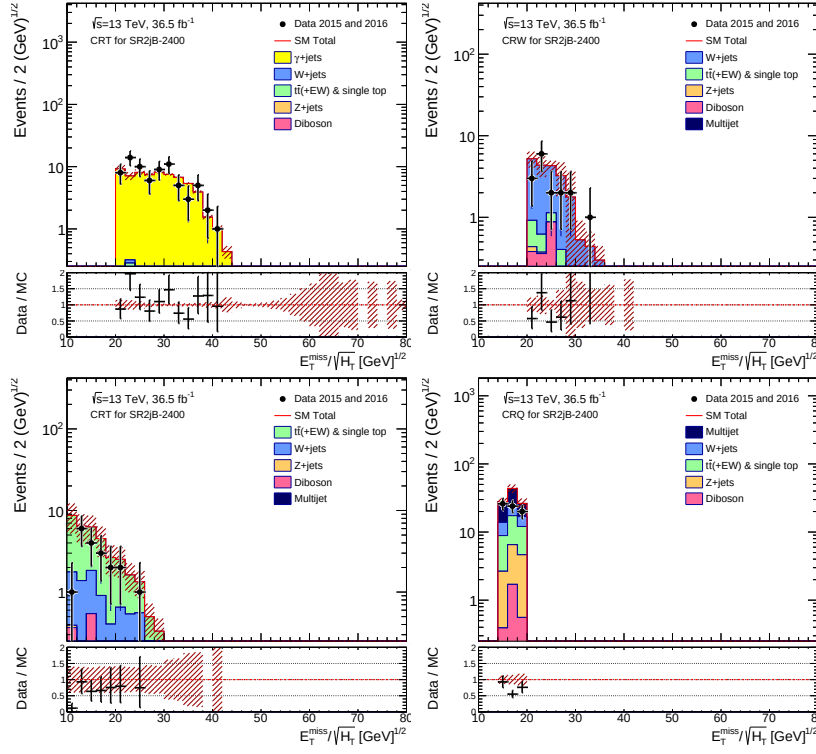


Figure 100: Observed  $E_T^{\text{miss}}/\sqrt{H_T}$  distributions in **2JB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

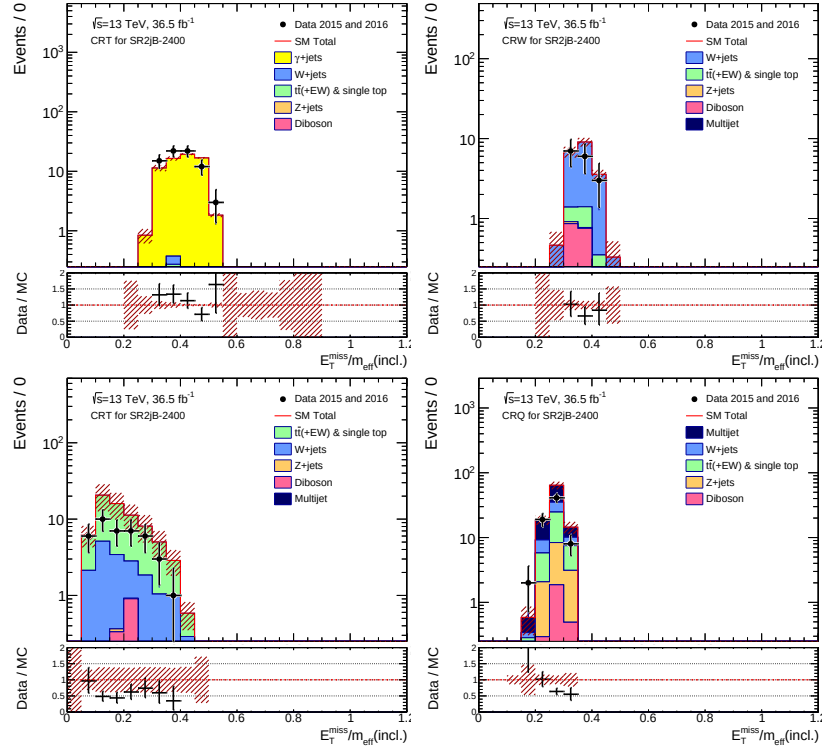


Figure 101: Observed  $E_T^{\text{miss}}/m_{\text{eff}}(2j)$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.



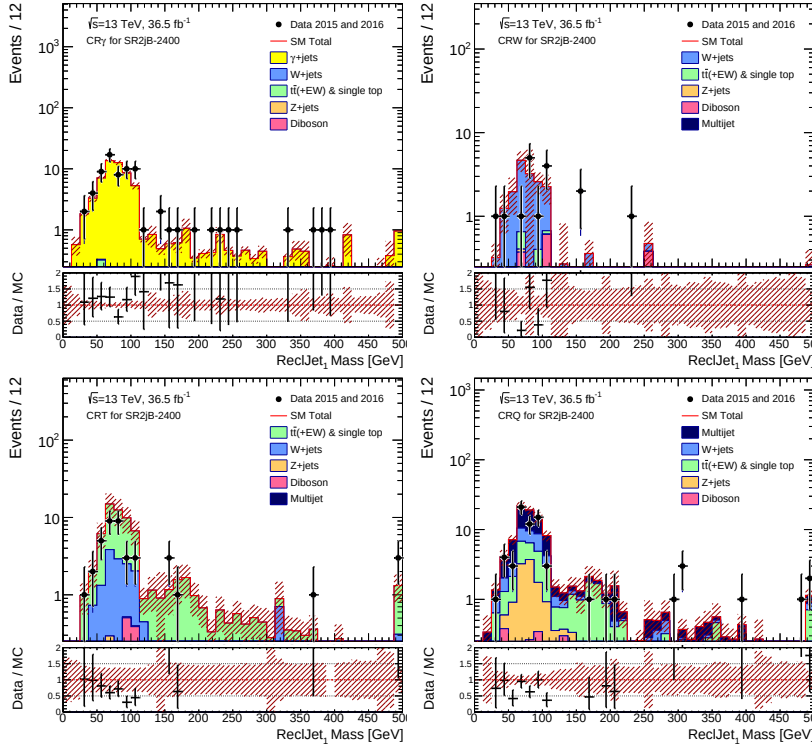


Figure 102: Observed  $m(R_{j1})$  distributions in **2JB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

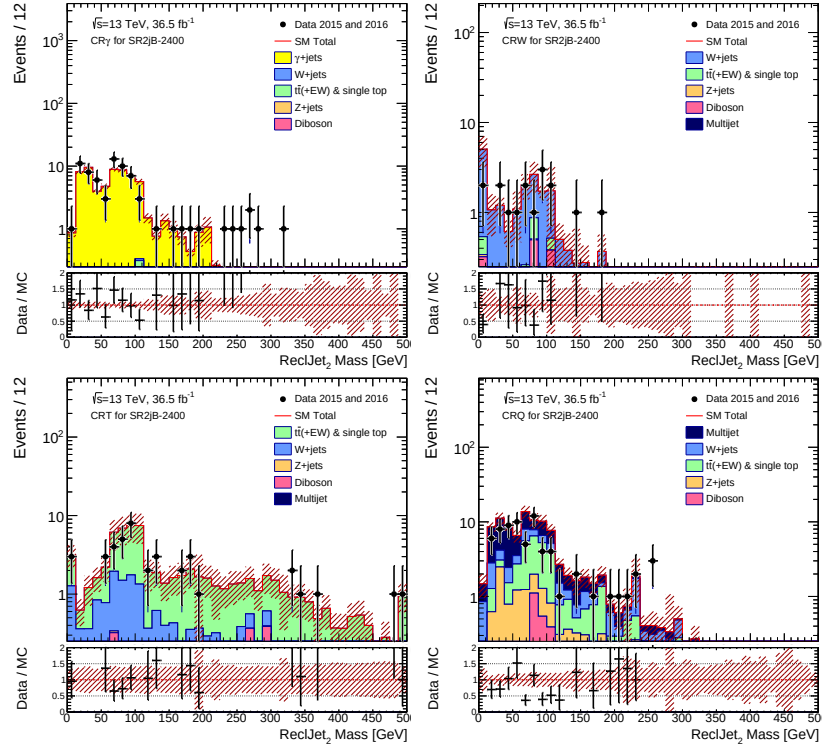


Figure 103: Observed  $m(R_{j2})$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

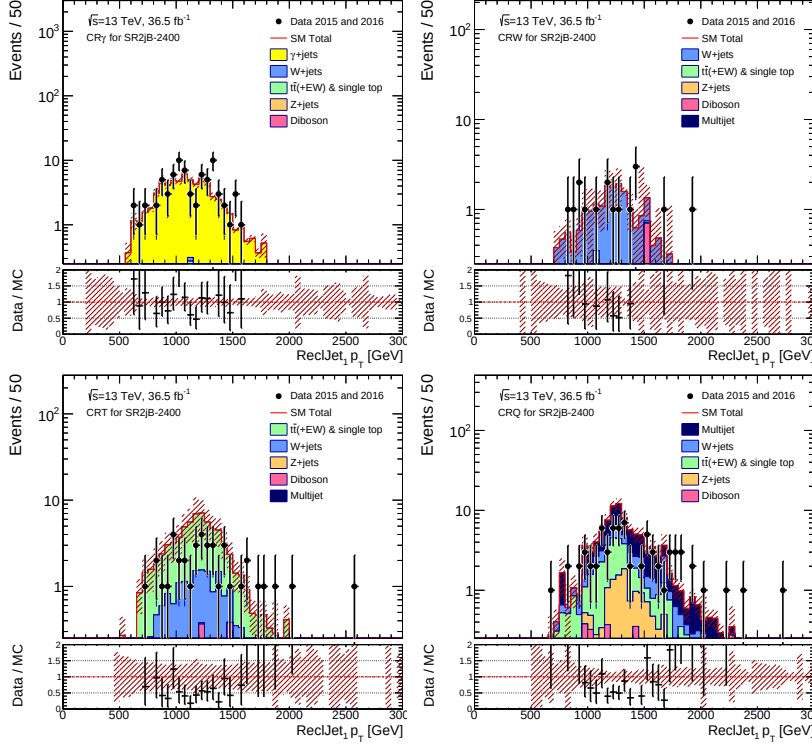


Figure 104: Observed  $p_T(R_{j1})$  distributions in **2JB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

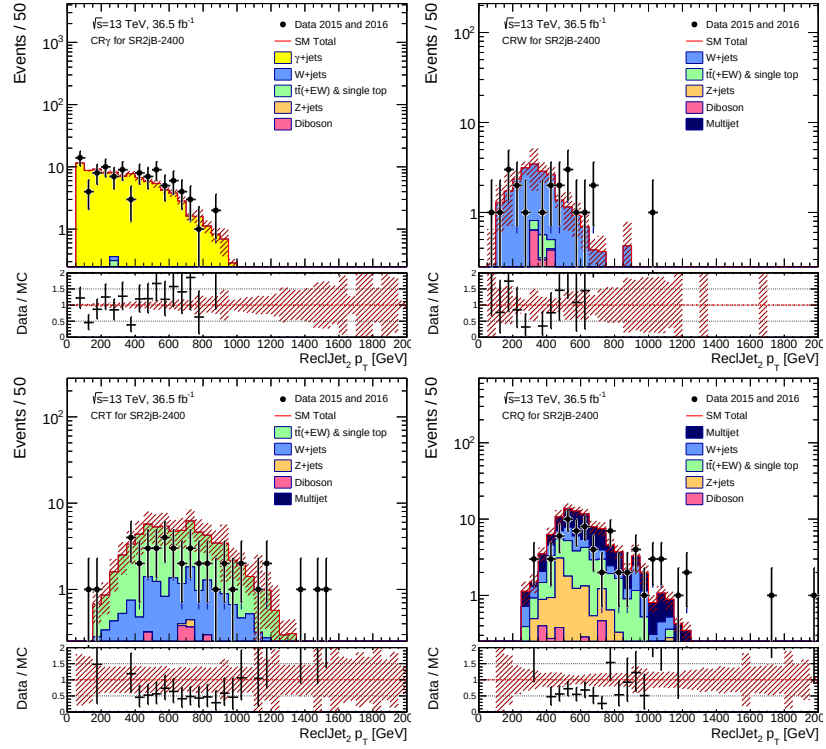


Figure 105: Observed  $p_T(R_{j1})$  distributions in **2jB-2400** control regions CRY (Upper left), CRW (Upper right), CRT (Lower left), CRQ (Lower right). The histograms denote the MC background expectations, normalised to luminosity. Cross-sections are the nominal one introduced in Section 7.2, except that  $\gamma$ +jets has been scaled by the  $\kappa$  factor defined in Section 7.9.1.

## MULTIJET BACKGROUND ESTIMATION BASED ON $E_{T,\text{track}}^{\text{miss}}$

In the context of the previous 0-lepton analysis done with  $20.3 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at 8 TeV [3], a data-driven method has been studied in order to provide an independent QCD background estimation in the signal regions. The method relies on constructing an ABCD grid in the  $(\Delta\phi(E_T^{\text{miss}}, E_{T,\text{track}}^{\text{miss}}), \Delta\phi_{\min}(\text{jet}, E_T^{\text{miss}}))$  plane.

The interest for an alternative method arose from some issues detected in the baseline method for multijet background estimation in the 0-lepton analysis performed at Run1, the *jet smearing* data-driven method described in this work (in its Run2 version) in Section 7.9.4. At the time of the Run1 analysis, the jet smearing method suffered of high systematic uncertainties and provided kinematical distributions of the multijet background with rather big disagreement with data in the dedicated control region. The method has been meanwhile revisited and subjected to large improvements towards its use in the Run2 analyses.

### B.1 INTRODUCTION

The  $E_{T,\text{track}}^{\text{miss}}$  variable, also called track- $E_T^{\text{miss}}$ , is defined as:

$$\vec{E}_{T,\text{track}}^{\text{miss}} = - \sum_{\text{track} \in \text{PV}} \vec{p}_T^{\text{track}} \quad (112)$$

where  $\vec{p}_T^{\text{track}}$  is the momentum of the tracks of charged particles measured in the tracking system. Such variable provides an independent measurement of the energy of the undetected particles with respect to the usual  $E_T^{\text{miss}}$  ([223]) based on calorimetric energy measurements. Differently to the  $E_T^{\text{miss}}$ , it does not take into account the energy carried by the neutral components of the jets coming from hadronization.

The  $E_{T,\text{track}}^{\text{miss}}$  variable can be used for discriminating multijet events from the signal ones. When the measured  $E_T^{\text{miss}}$  is real,  $E_{T,\text{track}}^{\text{miss}}$  will point in the same direction as  $E_T^{\text{miss}}$ . On the contrary, in multijet events the two variables have different origins, causing a different expected angular correlations.

In the dijet case,  $E_T^{\text{miss}}$  is originating from jet energy mis-measurements and will tend to be aligned to the energy fluctuating jet. On the other hand,  $E_{T,\text{track}}^{\text{miss}}$  will come from fluctuations in the fraction of energy carried by charged particles inside the jet after jet hadronization. Therefore,  $E_{T,\text{track}}^{\text{miss}}$  will point in the direction of the jet with the smallest fraction of charged particles, which is independent from the measured jet energy in the calorimeters. The result is that in QCD dijet events, the angle between  $E_T^{\text{miss}}$  and  $E_{T,\text{track}}^{\text{miss}}$  will then show a symmetric-like behaviour, different from the aligned behaviour of non-QCD events with real- $E_T^{\text{miss}}$ .

In the QCD multijet event case the energy is mostly carried by the two most energetic jets, which will tend to be back-to-back. The  $\Delta\phi(E_T^{miss}, E_{T,track}^{miss})$  should show the previous recognizable behaviour also for QCD multijet events.

## B.2 THE ABCD METHOD

The ABCD grid is defined by a pair of cuts in the  $(\Delta\phi(E_T^{miss}, E_{T,track}^{miss}), \Delta\phi_{\min}(\text{jet}, E_T^{miss}))$  plane, as shown by the sketch in Figure 106. From now on, the  $\Delta\phi_{\min}(\text{jet}, E_T^{miss})$  will be noted only as  $\Delta\phi$ .

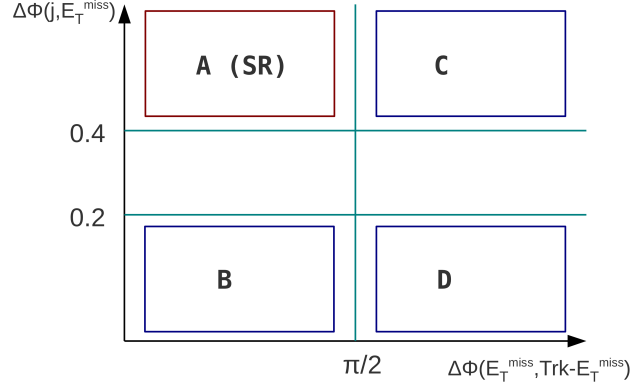


Figure 106: Different regions in the ABCD method in the plane of two variables  $\Delta\phi(E_T^{miss}, E_{T,track}^{miss})$ ,  $\Delta\phi$ . The cut in  $\Delta\phi$  defines the actual CRQ( $\Delta\phi < 0.2$ ), VRQ( $0.2 < \Delta\phi < 0.4$ ) and SR( $\Delta\phi > 0.4$ )

If there is enough statistics in the control regions B, C, D, then it is possible to estimate the small QCD yield  $N_A^{QCD}$  in the signal region A, by using the following formula:

$$N_A^{QCD} = \frac{N_B \cdot N_C}{N_D} \quad (113)$$

where  $N_{B,C,D} = N_{B,C,D}^{Data} - N_{B,C,D}^{SMMC}$ . Therefore, we estimate the QCD background as the difference between the observed data and all Standard Model Monte Carlo (SMMC), without the QCD simulated events contribution.

The method makes several assumptions:

1. There are enough events in regions B, C and D to propagate the statistical uncertainty linearly to A;
2. The background can be considered as coming from a single source (i.e. the well-known SMMC background is subtracted from the observations);
3. There are no correlations between the variables for the background in question;

The  $\Delta\phi(E_T^{miss}, E_{T,track}^{miss})$  and  $\Delta\phi$  variable distributions with no cut on its own value are shown in Figure 107, for an inclusive selection with  $N_{jets} \geq 2$ :

**Top**  $\Delta\phi(E_T^{\text{miss}}, E_{T,\text{track}}^{\text{miss}})$  is shown in regions A+C and B+D.

**Bottom**  $\Delta\phi$  is shown in regions A+B and C+D.

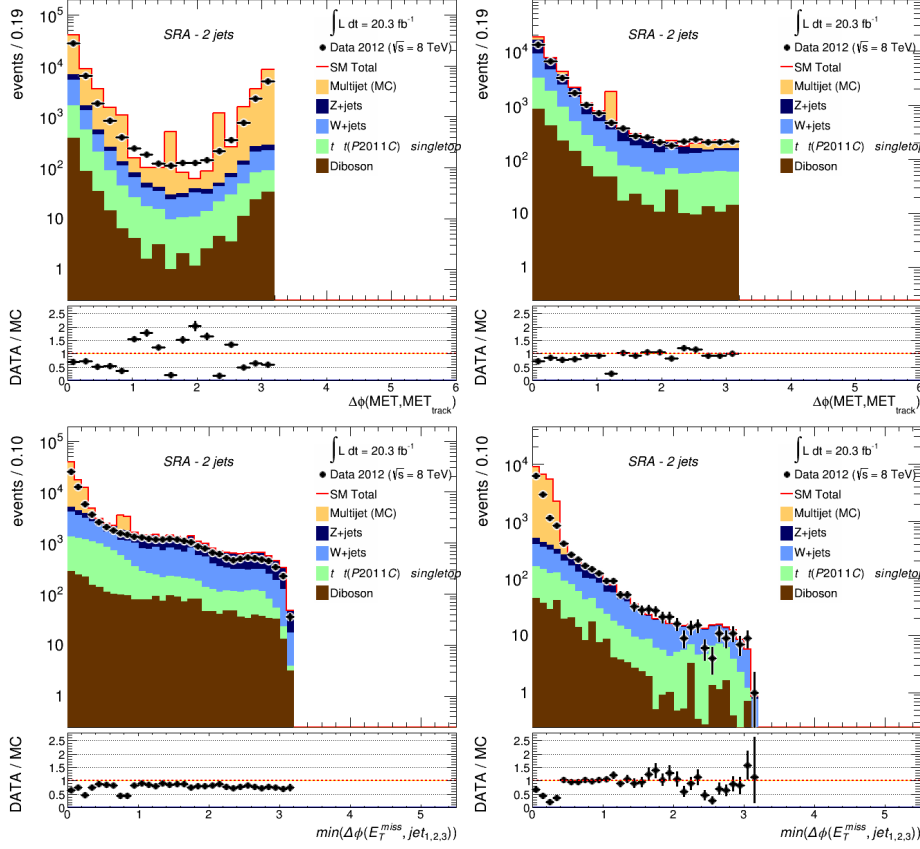


Figure 107: Comparison of the observed and predicted distributions of  $\Delta\phi(E_T^{\text{miss}}, E_{T,\text{track}}^{\text{miss}})$  after all cuts but on  $E_T^{\text{miss}}/m_{\text{eff}}$ , for 2-jets with  $\Delta\phi < 0.2$  (upper-left) and  $\Delta\phi > 0.4$  (upper-right). Comparison of the observed and predicted distributions of  $\Delta\phi$  after all cuts but  $E_T^{\text{miss}}/m_{\text{eff}}$  cuts for 2 jets with  $\Delta\phi(E_T^{\text{miss}}, E_{T,\text{track}}^{\text{miss}}) < \pi/2$  (bottom-left) and  $\Delta\phi(E_T^{\text{miss}}, E_{T,\text{track}}^{\text{miss}}) > \pi/2$  (bottom-right).

### B.3 RESULTS AND CONCLUSION

Preliminary numbers of QCD multi-jets events obtained with the ABCD method are shown in the Table 24 for the different signal regions of the analysis defined in [3]. We set a systematic error on the QCD by varying the MC yield by 30% in each of the B,C,D region before making the difference with the observed data and then propagating the errors towards the region A (Signal Region). The results are compared with the QCD yield estimated by the jet smearing method in almost all regions.

The total uncertainty on the track- $E_T^{\text{miss}}$  based method is dominated by the statistical uncertainties in region C of the ABCD grid, region where the QCD contribution is small in comparison to other processes

| Signal Region | Track MET yield                                         | Jet smearing method            |
|---------------|---------------------------------------------------------|--------------------------------|
| 2j loose      | $273.20 \pm 40.93(\text{stat}) \pm 301.01(\text{syst})$ | $115.38 \pm_{115.38}^{140.35}$ |
| 2j medium     | $-1.08 \pm 1.35(\text{stat}) \pm 4.05(\text{syst})$     | $0.41 \pm_{0.41}^{1.37}$       |
| 2j tight      | $-0.28 \pm 0.37(\text{stat}) \pm 0.41(\text{syst})$     | $0.14 \pm_{0.14}^{0.44}$       |
| 4j veryloose  | $33.60 \pm 7.13(\text{stat}) \pm 38.78(\text{syst})$    | $1.69 \pm_{3.94}^{1.69}$       |
| 4j loose      | $13.94 \pm 4.04(\text{stat}) \pm 15.67(\text{syst})$    | $0.73 \pm_{0.73}^{1.57}$       |
| 4j medium     | $0.04 \pm 0.39(\text{stat}) \pm 0.22(\text{syst})$      | $0.0 \pm 0.0$                  |
| 4j tight      | $-0.15 \pm 0.25(\text{stat}) \pm 0.07(\text{syst})$     | $0.0 \pm 0.0$                  |
| 5j medium     | $0.00 \pm 0.00(\text{stat}) \pm 0.00(\text{syst})$      | $0.99 \pm_{0.99}^{2.64}$       |
| 6j loose      | $9.14 \pm 5.60(\text{stat}) \pm 9.38(\text{syst})$      | $1.71 \pm_{1.71}^{2.95}$       |
| 6j medium     | $1.32 \pm 2.01(\text{stat}) \pm 2.36(\text{syst})$      | $0.44 \pm_{0.44}^{0.84}$       |
| 6j tight      | $-0.06 \pm 0.30(\text{stat}) \pm 0.10(\text{syst})$     | $0.01 \pm_{0.01}^{0.03}$       |
| 6j verytight  | $0.17 \pm 0.54(\text{stat}) \pm 0.42(\text{syst})$      | $0.25 \pm_{0.25}^{0.39}$       |

Table 24: Preliminary results table for QCD background rate in the SRs and their comparison to the baseline QCD jet smearing method. Only regions where the QCD multi-jets backgrounds is non null are specified.

because of the hard cut on  $\Delta\phi$ . Only in very loose SRs the systematic uncertainties play important role. Therefore other systematic uncertainties related to this method have been neglected so far. Given the large uncertainties ( $> 100\%$ ), present in both the track- $E_T^{\text{miss}}$  and jet smearing methods, no discrepancy can be claimed.



## LIMITS ON METASTABLE GLUINOS FROM ATLAS SUSY SEARCHES AT 8 TEV

Several SUSY models predict non-prompt decays of the gluino, which can therefore have rather long or very long lifetimes. Dedicated searches optimised on a signature of a long-lived gluino decaying outside the detector or stopping inside the detector have been conducted by ATLAS and CMS since the start of the LHC [224, 225].

After the publication of the analyses using final states with jets and  $E_T^{\text{miss}}$  in final state, based on  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions at 8 TeV recorded by ATLAS in 2012 (Run1), a re-interpretation with a model of metastable gluinos decaying in flight inside the detector has been performed on the same dataset.

The study provided the first limits on a scenario of metastable gluino produced by ATLAS. It employs the signal regions defined by two different analyses investigating the final state with  $E_T^{\text{miss}}$  and different multiplicity of jets: the "0-lepton" analysis with 2-6 jets [3] and the "Multijets" analysis with 7-10 jets in the final state [226].

The work has been performed by the author for the 0-lepton part, together with Miriea Crispin and Anna Sfyrla for the Multijets part in 2014. It is publicly available in Ref. [2].

### C.1 MOTIVATION AND MODELS

A beyond Standard Model scenario called *mini-split* SUSY [227] predicts squark masses around  $10^3 - 10^5 \text{ TeV}$  for small values of  $\tan\beta$ , as shown in Figure 108 (left). Given these squark masses, a 1 TeV gluino can be metastable and decay within the detector, as depicted in Figure 108 (right).

The model here investigated assumes the hadronization of the colored gluinos into a colorless  $R$ -hadron and sets the ratio of singly-charged to neutral  $R$ -hadrons to be close to 1, following LHC standards. The model considers two decay types of the gluino within the  $R$ -hadron:

- $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ , which would be the dominant decay if the top squark were the lightest squark;
- $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ , where  $q \neq t$ , which is a radiative process predicted for a mass-degenerate squark flavor scenario, or via  $\tilde{g} \rightarrow g\tilde{\chi}_1^0$ .

### C.2 SIMULATED SAMPLES

The signal samples are simulated using PYTHIA 6.427 [126] with CTEQ6L1 parton distribution functions. The cross sections are calculated at NLO+NNL in  $\alpha_S$ , defined in Section 4.1.2. The simulated samples have gluino

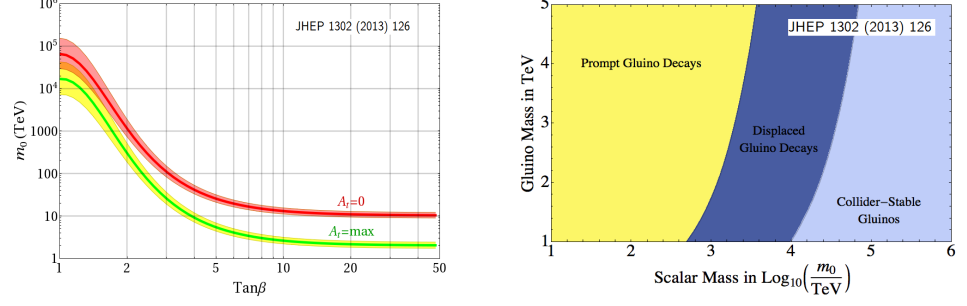


Figure 108: Left: Scalar SUSY masses needed to be consistent with the observed Higgs boson mass, as a function of  $\tan\beta$ , for large and small top mixing ( $A_t$ ). Right: Region of displaced gluino decays (metastable gluinos) as a function of scalar SUSY mass as a function of gluino mass. The figures are taken from [227].

masses in the range 400-1400 GeV and  $\tilde{\chi}_1^0$  masses in the range 200-1300 GeV. The gluino lifetimes considered are in the range of 1-10 ns, with some points up to 5  $\mu\text{s}$ .

The simulation of R-hadron interactions with the detector material is handled by a special detector response simulation using GEANT4 [136]. The R-hadron decays are also simulated with PYTHIA, after being propagated in GEANT4. The simulated events proceed through the ATLAS event reconstruction, as described in Section 4.3, which includes the pile-up re-weighting relative to the 2012 data taking.

### C.3 ANALYSIS AND RESULTS

Searches for SUSY strong production in final states with jets and  $E_T^{\text{miss}}$  can be sensitive to metastable gluino decays even though their signal regions are originally designed to look for promptly decaying SUSY particles. Gluinos decaying before the calorimeter may be observed by searches using high-energy jets as the 0-lepton. Searches selecting on b-jets as the Multijets can identify displaced jets when coming from metastable gluino decays, when the R-hadron decay radius is not too long or alternatively before the b-jets reconstruction efficiency critically drops. Moreover, for the considered R-hadron lifetimes, the trigger efficiency are still very high to not loose most of the signal events, while for longer lifetimes the signal acceptance is much reduced because of the trigger.

The reinterpretation is performed by applying the analysis selection on the signal models described above and extracting the yields. The sources of systematic uncertainties as well as the procedures used to extract them are the same as employed by the referenced analyses. No additional systematic uncertainties are considered in this reinterpretation. The dominant sources of systematic uncertainty on the signal generally arise from the JES and resolution uncertainties.

The resulting 95% confidence level (CL) exclusion limits on the gluino masses with fixed mass of the  $\tilde{\chi}_1^0$  are shown in Figure 109, while limits on  $\tilde{\chi}_1^0$  for fixed mass of the gluino are shown in Figure 110. In each figure, the limits on both the two gluino decay models to  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  /  $\tilde{g} \rightarrow g\tilde{\chi}_1^0$  (top) and to  $t\bar{t}\tilde{\chi}_1^0$  (bottom) are shown.

The expected exclusion limits are shown for the 0-lepton and Multijets analysis separately, together with the expected and observed combined results. The combination of the two searches is done choosing the best expected limit at each point in parameter space. The black points indicate the parameters of the simulated samples used to draw the limit curves, which are only displayed within the boundary of the simulated points. This study shows that sensitivity is still expected for lower masses of  $\tilde{g}$  and  $\tilde{\chi}_1^0$  and for longer or shorter lifetimes than was simulated.

#### C.4 DISCUSSION AND CONCLUSION

In general, the 0-lepton analysis has better sensitivity to the gluino decays to  $q\bar{q}\tilde{\chi}_1^0/g\tilde{\chi}_1^0$  as relatively small multiplicity of jets are expected, while in the gluino decays to  $t\bar{t}\tilde{\chi}_1^0$  both the 0-lepton and the Multijets analyses have good sensitivity. The sensitivity drops quickly for long lifetimes due to the original design of the analyses employed. In comparison with the limits set on prompt-decays by the 0-lepton analysis using the same dataset, the result already drops from  $\sim 1400$  GeV [3] to  $\sim 1200$  GeV for the shorter lifetime considered in the metastable case, with the same fixed  $m_{\tilde{\chi}_1^0} = 100$  GeV. Particularly, the effects of the analysis selection cuts on various samples, which can be found in Ref [2], shows some interesting features: events with lifetime longer than 1 ns have lower jet multiplicity, as gluino decays within or outside the calorimeter; at longer lifetimes, events with leptons in final state such as coming from  $t\bar{t}\tilde{\chi}_1^0$  decays fail the lepton veto, because leptons significantly displaced are not identified; some event cleaning cuts on the charged fraction or the EM energy fraction, essentially similar to those described in Section 7.6.1, cause the largest drop in the acceptance as they were originally designed against the cosmic/beam events; the b-tagging used in the Multijets analysis enhances the acceptance for small gluino lifetimes as jets are more often reconstructed as b-jets.

Concluding, the first ATLAS re-interpretation of two searches for strongly produced SUSY particles in terms of metastable gluino model has been presented. The re-interpretation has been performed on  $20.3 \text{ fb}^{-1}$  of pp collisions at 8 TeV recorded by ATLAS in 2012. The gluino is excluded up to  $m_{\tilde{g}} = 850(900)$  GeV for decays to  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  /  $\tilde{g} \rightarrow g\tilde{\chi}_1^0(t\bar{t}\tilde{\chi}_1^0)$ , for a lifetime of 1 ns and a fixed  $m_{\tilde{\chi}_1^0} = 100$  GeV. The interest in these models is still present within the ATLAS collaboration and a novel re-interpretation using the Run2 0-lepton analysis presented in this thesis was on-going at the time this thesis has been prepared.

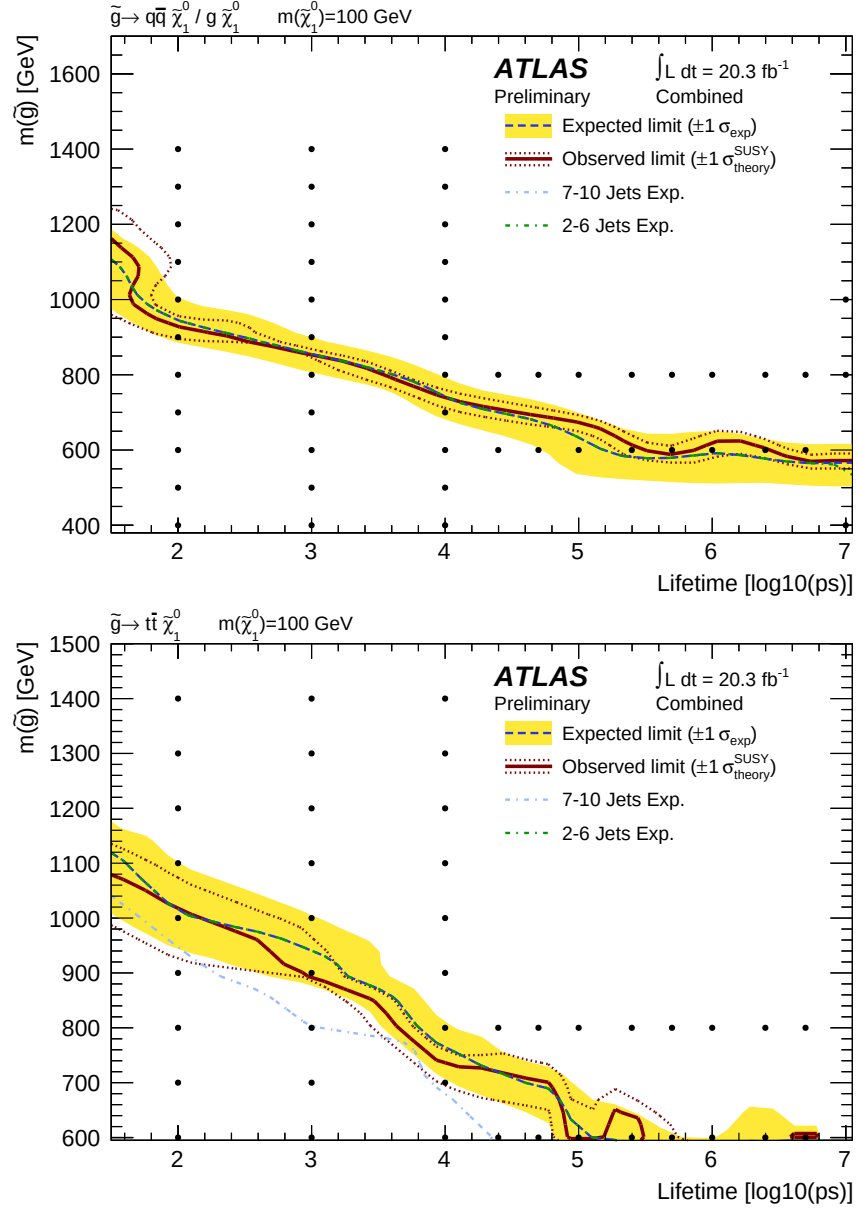


Figure 109: 95% CL exclusion limits on gluino mass as a function of gluino lifetime, for fixed  $m_{\tilde{\chi}_1^0} = 100$  GeV in the case of gluino decaying to  $q\bar{q}\tilde{\chi}_1^0/\tilde{g} \rightarrow g\tilde{\chi}_1^0$  (top) and to  $t\bar{t}\tilde{\chi}_1^0$  (bottom).

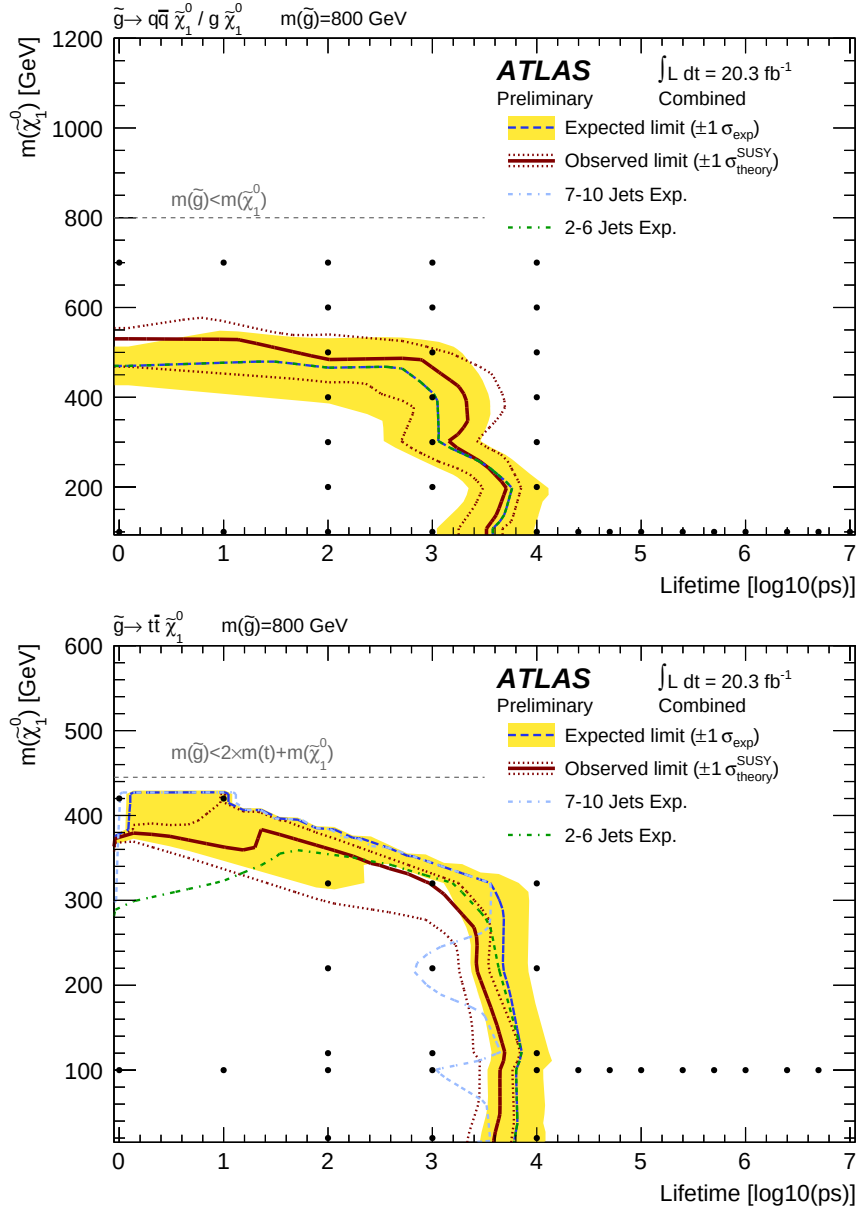


Figure 110: 95% CL exclusion limits on  $\tilde{\chi}_1^0$  mass as a function of gluino lifetime, for fixed  $m_{\tilde{g}} = 800$  GeV in the case of gluino decaying to  $q\bar{q}\tilde{\chi}_1^0/\tilde{g} \rightarrow g\tilde{\chi}_1^0$  (top) and to  $t\bar{t}\tilde{\chi}_1^0$  (bottom).



## Part V





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