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Mireia Crispín Ortuzar

# High Jet Multiplicity Physics at the LHC

Doctoral Thesis accepted by
the University of Oxford, UK

Springer

*Author*
Dr. Mireia Crispín Ortuzar
Memorial Sloan Kettering Cancer Center
New York, NY
USA

*Supervisor*
Prof. Alan J. Barr
Department of Physics
University of Oxford
Oxford
UK

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*We are a way for the Cosmos to know itself*

Carl Sagan

*A mis padres, Vicente y Visi;*
*a mi hermano, Marcos;*
*y a Tomeu*

# Supervisor's Foreword

People have been curious about what matter is made of for millennia. It is one of the insights of modern science that the material objects around us can all be described as collections of point-like particles. They in turn behave according to the charmingly understated "Standard Model" of particle physics. Building that theory was the result of decades of work, both experimental and theoretical, in the latter part of the twentieth century. The experimental discovery of the Higgs boson particle in 2012, almost 50 years after it was theoretically predicted, was powerful demonstration both of the predictive power of the Standard Model, and the degree to which it has been subject to rigorous tests.

Yet, despite its manifest successes, the Standard Model falls short of perfection in certain crucial aspects. Most strikingly, astronomical observations show there is far from enough Standard Model matter in galaxies to explain their mutual gravitational attractions. The same shortfall in mass is found for clusters of galaxies or other larger-scale structures. Some other particles, as yet undetected on earth, and not part of the Standard Model, must be gravitationally binding these very large objects together.

A huge number of candidate theories have been proposed to explain the Dark Matter. In these expanded theories, particles not present in the Standard Model are introduced. Those particles are proposed to be produced in the early universe, and to persist with enough mass density to explain the additional gravitational attractions within and between galaxies. The result is a profusion of possible theories, and a breakdown in predictability. Only careful experiments and observations can tell us which—if any—of these candidate theories might surpass the Standard Model as the new best description of the universe.

So how can we proceed? Our understanding of Dark Matter would be transformed if we could produce this elusive stuff in the laboratory. That might seem a tall order, but making particles out of the nothingness of the vacuum is by now standard practice in particle physics. The cost, which can be calculated using Einstein's theory of special relativity, is that to make new particles we must have sufficient energy. The highest energy densities on earth are found at the Large

Hadron Collider (LHC), so it was therefore to this 27 km-long collider, in CERN, near Geneva, that we turned to peruse our Dark Matter quarry.

This is perhaps a good time to introduce Mireia Crispín Ortuzar. By the time she came to Oxford for doctoral studies, she had already gained substantial academic experience in Spain, the USA, the UK, Canada, Germany, and CERN. She had worked on projects as diverse as gravitational wave searches, radio astronomy, and particle physics. With her she brought a long list of academic awards, and, more unusually, two undergraduate degrees, one in physics, and one in music. She quickly gained the respect of colleagues, not only in Oxford, but also from our collaborating institutes around the world, both for the quality of her research, and the clarity with which she communicated her results.

Unusually, Dr. Crispín Ortuzar's doctoral studies covered both of the main methods for pursuing new phenomena at the LHC—direct searches for new particles, and precision measurements of Standard Model processes. This breadth makes her thesis a superb introduction to the physics of the Large Hadron Collider.

Starting from an introduction to the Standard Model, she then proceeds to explain the key features of Large Hadron Collider, and the ATLAS detector. She then provides a systematic and detailed explanation of her search for Dark Matter production, starting from the initial design of the analysis, and describing each step towards to the final results. In the second main analysis chapter she describes in detail the precision measurement of a Standard Model process—in which several jets of particles are emitted from the same proton–proton collision. Again, each step of the procedure is laid out, from the initial motivation through to the final results. In doing so, Dr. Crispín Ortuzar has provided not just one, but two ideal case studies, each demonstrating how to perform cutting-edge science at the LHC.

The very existence of the LHC is a testament to the achievements of human endeavour. It will have much to teach us about the universe we live in for many decades to come. I trust that during that time the clarity and depth of this thesis will keep it of interest as much to experts in the field as to those starting out on their journey.

Oxford, UK Prof. Alan J. Barr
April 2016

# Preface

As a member of the ATLAS Collaboration I was involved in various projects, some of which are included in this thesis. The full list is included here in reverse chronological order, for completeness.

- **Measurements of four-jet differential cross sections from $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS experiment.** I led most of the aspects of the analysis. See Chap. 4 of this thesis. I was the main author and contact editor of the paper, published in 2015 in the Journal of High Energy Physics, issue 12, pp. 1–76.
- **Limits on metastable gluinos from ATLAS SUSY searches at 8 TeV.** I produced all the results corresponding to the multi-jet analysis (one of the two searches included in the note). Published in 2014 as the ATLAS note ATLAS-CONF-2014-037.
- **Performance of $E_{\mathrm{T}}^{\mathrm{miss}}$ at high luminosity.** I performed a new parametrisation of the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the high luminosity scenario, which has been used in the upgrade physics analyses since 2013. Part of the results were published in the ATLAS note ATL-PHYS-PUB-2013-009.
- **Search for new phenomena in final states with large jet multiplicities and missing transverse momentum at $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS experiment.** I was responsible for the stream of the analysis, described in Chap. 3 of this thesis. I performed the optimisation of the analysis strategy, calculated the signal and background contributions and uncertainties, and processed the data. See Chap. 3 of this thesis. Published in 2013 in the Journal of High Energy Physics, issue 10, pp. 1–50.
- **Searches for supersymmetry at the high luminosity LHC with the ATLAS detector.** I produced all the results for the strong production section. Published in 2012 as the ATLAS note ATL-PHYS-PUB-2013-002.

New York, USA
Dr. Mireia Crispín Ortuzar

# Abstract

The Large Hadron Collider at CERN completed its first data-taking phase in 2013, after 3 years of remarkable performance. The high-energy proton–proton collisions recorded by the ATLAS experiment provide a gateway to the world of subatomic particles. This thesis presents two analyses of the full 8 TeV dataset taken by ATLAS, inspired by two of the major physics goals of the experiment. The first analysis is a search for new phenomena that could explain the nature of Dark Matter and solve the hierarchy problem. In particular, the search is optimised to look for heavy supersymmetric particles decaying to large numbers (7 to $\geq 10$) of jets. The events are further classified according to the number of jets identified as originating from a $b$ quark. No evidence is found for physics beyond the Standard Model, so the results are interpreted in terms of exclusion limits on various simplified supersymmetry-inspired models where gluinos are pair produced, as well as an mSUGRA/CMSSM model. The main background to the search is due to multi-jet production via the strong force. This motivates the second analysis presented in this thesis, which is a measurement of the cross section of four-jet events. The measurement is performed differentially in a series of variables which describe the kinematics and spatial configuration of the events. The results are compared to existing theoretical predictions.

# Acknowledgements

First and foremost, I would like to thank Alan Barr, my supervisor, for guiding me through my DPhil. He is one of the most inspiring and brilliant scientists I know, an extremely supportive and attentive mentor, and the most efficient ATLAS member I have ever met.

My DPhil was funded by a combination of generous scholarships from the Caja Madrid Foundation, Balliol College (through a Foley-Béjar Scholarship), Telefonica and the British Spanish Society. I was also supported by the Particle Physics Sub-department of the University of Oxford, especially during my time in Geneva. I owe them a huge debt of gratitude.

I have had the pleasure of working with some great teams of physicists in the ATLAS Collaboration. I learnt a great deal from the wisdom and experience of Chris Young, Anna Sfyrla, Zach Marshall, and David Miller. Anna spent many hours with me in my first year, showing me the intricacies of the trigger system, and has remained an invaluable collaborator throughout my DPhil. I had the immense luck to work closely with Hernán Reisin on the SUSY multi-jet analysis, who made those long days of cutflow-checking actually joyful. Sabrina Sacerdoti followed on Hernán's steps in the Standard Model multi-jet measurement, responding to my hundreds of emails asking for more tests even in the middle of the holidays. I have also learnt a lot from Caterina Pizio and Paolo Francavilla, mostly about the details of the missing transverse momentum (and some very basic Italian). Daniel Maitre, Tuomas Hapola, and Simon Badger kindly provided additional theoretical predictions for the cross-section measurement.

The Oxford SUSY group provided the perfect working environment. Andrée Robichaud-Véronneau and Alex Dafinca were my consecutive officemates, and both answered all my annoying questions and made me look forward to getting in every morning. With Will Kalderon I discovered the first evidence for direct spanda production, and James Scoville patiently explained some of the subtleties of particle theory.

The IT officers at Oxford, in particular Sean Brisbane, have been incredibly helpful: they have maintained and upgraded the systems, responded to every single

request at any random time of the day or week, rescued lost files and helped run jobs on the cluster. This thesis could very well not exist without them.

Beyond my closest collaborators, I have been surrounded my a wonderful group of scientists both during my time in Oxford and in Geneva. My college tutor, Armin Reichold, has been a reference for me and a constant source of support. Kate and Nazim were my housemates for 2 years (and in two countries) and managed to turn our house into a home. The rest of the lovely Oxford group were always ready to discuss physics and have fun. My time in Geneva (and beyond) would not have been the same without Dani Cámpora and Tom Gillam. Both Dani and Tom filled my days with music, and there is not a piece of code I have which Tom has not saved from disaster at some point in time. At Balliol I have shared countless musical projects and precious moments with Hilary, Ben, Andrew, and many others.

I would not be here without the selfless, unconditional, and loving support that my parents, Visi and Vicente, have given me and my brother Marcos throughout my life. I embarked on this DPhil journey with Tomeu, and we have shared all the challenges and small victories. He has encouraged me beyond words, listened to every talk I have given and read every paper I have written with unshakable patience and love. This thesis is dedicated to the four of them.

# Contents

# Introduction

*'Explain all that,' said the Mock Turtle.*
*'No, no! The adventures first,' said the Gryphon*
*in an impatient tone: 'explanations take such a dreadful time.'*

Lewis Caroll, Alice's Adventures in Wonderland

The goal of particle physics is to understand the nature and interactions of the most elemental constituents of the universe, the fundamental particles. It is common for particle physics experiments to find out what things (particles) are made of by smashing them together and breaking them apart. As technology advances, particle accelerators and colliders reach higher and higher energies, which allows them to potentially produce increasingly heavier particles as part of the collision products. It is the particle physicists' job to reconstruct the full history of the interactions and decays happening in a collision, starting from a single electronic 'photograph' taken by the detector—the 'final state'. Particle detectors have allowed us to discover a plethora of particles, all of which fit nicely into the theoretical framework of the Standard Model. But there are a number of reasons why it is believed that this model is not complete, and that new particles must appear at the energy threshold of $\mathcal{O}$(TeV). The Large Hadron Collider (LHC) sits exactly on that energy frontier.

This thesis presents two analyses of the collision data measured by the ATLAS detector at the LHC. The two analyses may be seen as two sides of the same coin: both of them focus on the same type of final state particle configuration, but each has a different—though complementary—goal.

The events of interest for both analyses are those in which a large number of *jets* are produced. Jets are roughly conical sprays of particles, and they are omnipresent at the LHC. However, they present a number of challenges, both from the experimental perspective—as they are hard to reconstruct and calibrate—and from the theory point of view, because the complexity of the calculations grows rapidly with the number of jets in the final state. Why should we be interested in such a complicated scenario? The main reason is that new, very heavy and strongly interacting particles, of the sort that one would hope to be able to discover at the

LHC, decay in cascades producing large numbers of jets. Moreover, these types of events also provide an excellent ground in which to test the subtleties of the theory of strong interactions.

The first study (Chap. 3) is a direct search for new physics phenomena beyond the Standard Model. As in most searches for new particles, there may be other interactions happening in the detector that look just like what is being searched for; this ‘noise’ has to be either removed or modelled (or both), and we refer to it as ‘background’. The estimation of the multi-jet backgrounds will rely precisely on the mismeasurement of the energy of the jets, providing a way to describe some of the components of very high jet multiplicity environments without the need to resort to theoretical calculations. Although, alas, no new signals are found, strong limits are set on a variety of new physics models.

Searches for new particles cannot be successful unless their background processes are well understood; this is why it is useful to have direct measurements of Standard Model processes. The second study (Chap. 4) is a measurement of the cross section of four-jet events, studied as a function of several variables that describe the dynamics of the event. Cross sections tell us how likely it is that a particular process will occur in a way that is independent of some of the experimental details of the collision. The measurement presented here provides discrimination between different state-of-the-art theoretical calculations, which is useful to see where theories can be improved.

Chapters 1 and 2 will set the basic theoretical and experimental concepts needed for the rest of the thesis.