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Enrico Morgante

Aspects of WIMP Dark Matter Searches at Colliders and Other Probes

Doctoral Thesis accepted by
the University of Geneva, Switzerland

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Supervisor's Foreword

This thesis is a report of the work carried on by Enrico Morgante on the theoretical aspects of WIMP Dark Matter (DM) searches, with a particular emphasis on LHC physics. This constitutes the main topic on which his research has focussed so far, even if his interests and activity have spanned other topics in between particle physics and early universe cosmology.

As far as LHC searches are concerned, the present work starts with a critical discussion of the EFT approach, whose limitations were highlighted by our group in a series of papers which have had a major impact in the field. The techniques that we proposed to overcome these limitations and get sensible results in terms of effective operators—that are thoroughly described in the thesis—had become a standard tool for the LHC collaborations. The discussion then turns to simplified models, which are introduced and carefully analysed, paying attention to their consistent construction and use, which is essential in order to obtain reliable results, in particular when comparing results coming from different searches. An example of a simplified model is introduced and analysed, drawing conclusions whose relevance goes well beyond the particular model under scrutiny.

A chapter of the thesis is devoted to DM searches through cosmic rays, and in particular on the possibility of discovering a DM signal with a measure of the antiproton flux. It is pointed out that a possible antiproton signal may not be regarded as a smoking gun for DM annihilation in the halo because of its degeneracy with a purely astrophysical process in which secondary antiparticles are produced at the acceleration region of supernova remnants, resulting in a spectral shape very similar to that predicted by DM models. If such a signal is observed, further studies of this phenomenon would be necessary to disentangle it from the desired signal, taking into account the information from other complementary search channels.

An additional value of this thesis is given by its long and detailed introduction to the DM puzzle, its possible solutions and the experimental searches for WIMP DM. The introduction is complemented by precise references to the original works and to other review articles, which could serve as a useful reference for researchers active in the field and particularly for young researchers.

It gave me immense pleasure that the work of Enrico Morgante was selected by the University of Geneva and Springer to be published in the Springer theses series.

Geneva, Switzerland
June 2017

Antonio Riotto

Abstract

The problem of Dark Matter (DM) is one of the most longstanding problems in cosmology and particle physics, and surely one of the most interesting. A number of astrophysical and cosmological evidence point to the existence of a large amount of non-luminous matter, whose nature is still a mystery. The simplest possible solution to this puzzle is in terms of new neutral and stable particles with weak-scale mass and couplings (named WIMPs for weakly interacting massive particles), which would not only reproduce naturally the observed cosmological DM abundance, but also fit very well in many well-motivated theories for physics beyond the standard model. In this thesis, I discuss the present status of WIMP searches and of our understanding of the theoretical issues involved in them, with a particular emphasis to searches at the Large Hadron Collider.

Preface

Among the natural sciences, the oldest is probably astronomy. Its origins date back to the rise of the first civilizations, when astronomical observations allowed for producing the first calendars. For thousands of years, cosmogonies were directly related to religious beliefs, showing a connection with the deepest questions of human heart that keep fascinating generations of modern scientists. It was not until the seventeenth century that astronomy started assuming its present aspect, thanks to the pioneers Nicolaus Copernicus, Galileo Galilei, Tycho Brahe, Johannes Kepler and Isaac Newton. It was due to their work that we understood that the orbits of celestial bodies are governed by mathematical relations; if any deviation is seen, either new, unseen objects are present to modify the equation of motion, thanks to their gravitational attraction, or a modification of the laws of gravity is necessary for some regime.

An example of the first approach is the discovery of Neptune, the eighth planet of the Solar System, whose existence was hypothesized by Urbain Le Verrier and, independently, by John Couch Adams in 1846, in order to account for the anomalous motion of Uranus. Neptune was first observed by Johann Galle and Heinrich d'Arrest of the Berlin Observatory on 23 September of the same year, the same night when Galle received a letter from Le Verrier asking to confirm his predictions. Neptune was found within 1° of the predicted location, providing a strong confirmation of the laws of celestial mechanics. The second approach proved to be useful in the case of another planet, Mercury. The precession of its orbit was reported by Le Verrier himself, who pointed out in 1859 that its characteristics were at odds with the Newtonian laws of gravitation. His faith in Newtonian mechanics, and the success with Neptune, suggested him that the solution could be a new unseen planed (which he named Vulcan) or a series of smaller "corpuscules". These attempts proved to be unsuccessful, and the explanation was finally provided by Albert Einstein in 1916, with the introduction of the theory of General Relativity.

The problem of DM is conceptually not different from that of the motion of planets in the Solar System. A number of anomalies were observed, starting back in 1933, from the galactic scales to that of the largest structures, that can be explained only by the existence of some new non-luminous component which constitutes more than 80% of the total mass of galaxies and galaxy clusters, or else by some further modifications of General Relativity. Which of the two solutions is the correct one is still matter of debate, even if a modification of the matter content is commonly regarded as more likely, due to the difficulty of modified gravity theories of deal with the formation of large-scale structures. Furthermore, it is a well-established result that exotic astrophysical objects can only constitute a small fraction of the total DM content of the Universe, with only some small windows left open by astrophysical observations. Because of this, the most plausible solution to the puzzle seems to be in the form of subatomic particles, and DM can be regarded as a particle physics problem as well as an astrophysical one.

Our present understanding of particle physics is based on the so-called Standard Model (SM), which describes the interactions of all the known elementary particles in terms of a $SU(3) \times SU(2) \times \mathrm{U}(1)$ gauge symmetry, spontaneously broken to the $SU(3) \times \mathrm{U}(1)$ symmetry of the strong and electromagnetic interactions. Given the fact that DM is stable and that it does not seem to interact electromagnetically, the only DM candidate in the SM is the neutrino. As we will see in Sect. 1.3, neutrinos cannot account for all the DM, and the introduction of new stable particles is necessary.

Two very exciting facts occur at this point. On the one hand, a simple calculation of the relic abundance of DM in the thermal hot Big Bang scenario indicates that a particle with a mass around the weak-scale and weak coupling strength would have the right present-day abundance. This coincidence is often referred to as the “WIMP miracle”, for *weakly interacting massive particle*. On the other hand, the SM suffers from the so-called “Higgs naturalness problem”, which is the fact that the electro-weak scale is unstable against quantum corrections and, assuming the point of view that the SM is just the low energy limit of some more fundamental physics, maybe at the Plank scale, a very fine-tuned choice of the parameters is necessary in order for the EW scale to remain light. Solutions to this problem typically involve new physics at the TeV scale, as in the case of phenomenological supersymmetric models as the MSSM, in extra dimension theories as the Arkani-Hamed, Dimopoulos & Dvali model or the Randall-Sundrum one, *etc.* Interestingly, most of these theories include quite naturally stable neutral particles, with the right quantum numbers and properties to be a perfectly suitable WIMP candidate.

These two observations together catalysed a huge attention in the last decades around the WIMP DM paradigm and the experimental techniques for a possible detection. A number of probes exist to test the WIMP hypothesis. They are most commonly classified as direct, indirect and collider searches. Direct WIMP searches look for tiny energy deposits when DM particles of the galactic halo scatter off atomic nuclei in ultra-sensitive, low-background underground detectors. Indirect searches instead aim at observing annihilation products of DM particles such as neutrinos, antiprotons, positrons and gamma rays from galactic regions of increased density. Finally, collider searches look for the production of DM particles among the final states of proton–proton collisions (in the case of the LHC). In the collider setup, DM particles leave no trace in the detector and show themselves as unpaired momentum in the centre of mass frame, with the recoil of some SM particles which are necessary to tag the event.

In order to experimentally constrain the properties of DM, it is necessary to fix a reference model to compare with data. As we will discuss in detail in Sect. 5.3, this is not a trivial task in general. In direct searches, the very low momentum transfer involved in the scattering process allows one to write down a set of non-relativistic effective operators which capture all the possible feature of the DM–nucleons interaction in any DM model. Limits are therefore model independent, provided that the correct non-relativistic operator is considered. Quite the opposite happens at colliders: the very high-energy reach (larger than the naïve WIMP energy scale) makes it of primary importance to carefully consider which is the best model to consider: on the one hand, searches can be built to constrain the parameter space of beyond the Standard Model (BSM) theories as the MSSM or other realizations of supersymmetry. On the opposite side of the spectrum, one can rely on a set of effective operators, taking into account the strong limitations posed by the fact that, for an Effective Field Theory (EFT) approach to be valid, the energy involved in the process must be smaller than the Wilson coefficient of the operators. Finally, somehow in between of these two approaches, one can construct a set of simplified models, in which the SM is complemented with a DM candidate and some particle to mediate the DM interactions, in such a way to avoid the energy limitations of the EFT approach and to grasp the most relevant features of a given BSM model.

This thesis is organized as follows: in Chap. 1, we will introduce the DM problem by reviewing; in Sect. 1.1 the observational evidences of the existence of DM; in Sect. 1.2 the possible mechanisms for obtaining the present relic DM abundance in the early universe; in Sect. 1.3 the most studied DM candidates from BSM theories.

In Chaps. 2 and 3, we will introduce direct and indirect DM searches in general, and describe the present state of the art. In Chap. 4, we will discuss the implication of a signal in the antiprotons channel by the AMS-02, showing how this could not have been unambiguously attributed to DM annihilation events.

We will discuss DM searches at the LHC in Chap. 5. We will start by describing the characteristics of DM searches, with the prototypical example of the mono-jet one, and then discuss in general the three classes of DM models to which we referred above. The limitations of the EFT approach are described in Chap. 6. Chapter 7 contains a broad discussion on simplified DM models, complemented in Chap. 8 with a discussion of the role of the relic abundance calculation in the context of LHC searches.

In Chap. 9, we will consider a simplified model with a Z' additional gauge boson, and we will show how different experiments provide complementary bounds, highlighting in particular the role of the IceCube experiment in the context of spin-dependent DM–nucleon interactions. Our conclusions are then presented in the last chapter.

Hamburg, Germany Dr. Enrico Morgante

List of Publications

Publications Related to this Thesis

1. G. Busoni, A. De Simone, E. Morgante and A. Riotto, *On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC*, Phys. Lett. B **728** (2014) 412, http://arxiv.org/abs/1307.2253.
2. G. Busoni, A. De Simone, J. Gramling, E. Morgante and A. Riotto, *On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC, Part II: Complete Analysis for the s-channel*, JCAP **1406** (2014) 060, http://arxiv.org/abs/1402.1275.
3. G. Busoni, A. De Simone, T. Jacques, E. Morgante and A. Riotto, *On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC Part III: Analysis for the t-channel*, JCAP **1409** (2014) 022, http://arxiv.org/abs/1405.3101.
4. V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto and W. Xue, *Can AMS-02 discriminate the origin of an anti-proton signal?*, JCAP **1410** (2014) no.10, 078, http://arxiv.org/abs/1406.5377.
5. G. Busoni, A. De Simone, T. Jacques, E. Morgante and A. Riotto, *Making the Most of the Relic Density for Dark Matter Searches at the LHC 14 TeV Run*, JCAP **1503** (2015) no.03, 022, http://arxiv.org/abs/1410.7409.
6. E. Morgante, D. Racco, M. Rameez and A. Riotto, *The 750 GeV Diphoton excess, Dark Matter and Constraints from the IceCube experiment*, JHEP **1607** (2016) 141, http://arxiv.org/abs/1603.05592.
7. T. Jacques, A. Katz, E. Morgante, D. Racco, M. Rameez and A. Riotto, *Complementarity of DM Searches in a Consistent Simplified Model: the Case of Z'*, JHEP **1610** (2016) 071, http://arxiv.org/abs/1605.06513.

Other Journal Papers

1. M. Biagetti, A. Kehagias, E. Morgante, H. Perrier and A. Riotto, *Symmetries of Vector Perturbations during the de Sitter Epoch*, JCAP **1307** (2013) 030, http://arxiv.org/abs/1304.7785.
2. P. Ciafaloni, D. Comelli, A. De Simone, E. Morgante, A. Riotto and A. Urbano, *The Role of Electroweak Corrections for the Dark Matter Relic Abundance*, JCAP **1310** (2013) 031, http://arxiv.org/abs/1305.6391.
3. J. R. Espinosa, G. F. Giudice, E. Morgante, A. Riotto, L. Senatore, A. Strumia and N. Tetradis, *The cosmological Higgstory of the vacuum instability*, JHEP **1509** (2015) 174, http://arxiv.org/abs/1505.04825.

White Papers

1. J. Abdallah et al., *Simplified Models for Dark Matter and Missing Energy Searches at the LHC*, http://arxiv.org/abs/1409.2893.
2. J. Abdallah et al., *Simplified Models for Dark Matter Searches at the LHC*, Phys. Dark Univ. **9-10** (2015) 8, http://arxiv.org/abs/1506.03116.
3. D. Abercrombie et al., *Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum*, http://arxiv.org/abs/1507.00966.

Conference Proceedings

1. E. Morgante, *On the validity of the effective field theory for dark matter searches at the LHC*, Nuovo Cim. C **38** (2015) no.1, 32, http://arxiv.org/abs/1409.6668.
2. E. Morgante, *Cosmological History of the Higgs Vacuum Instability*, Frascati Phys. Ser. **61** (2016) 115.

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I am deeply indebted to my teacher Riccardo Sangoi, who first introduced me to the realm of science. I still remember the day when, aged 15, he made me compute the trajectory of a small iron sphere falling from his desk, asking me to measure the impact point on the ground and to compare it with my prediction: perfect agreement! Oh wonder! On that day I learned a lesson I will never forget: that physics is not just a long list of complicated formulas, but it is the journey towards those laws that exist behind our reality, a noble adventure that we have the privilege of living.

Finally, I want to thank my wife and my daughters, and also my parents for all they had done for me and for always supporting me. There are no words to express my gratitude to them.

Hamburg, Germany
June 2017

Enrico Morgante

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