On the Detection of Dark Matter

Likelihoods and limits on spin-independent and spin-dependent WIMP couplings and the implementation of radiative muon decays in dark matter analyses.

Andre Scaffidi

Center of Excellence for Particle Physics at the Terascale
School of Physical Sciences, Adelaide University.

University of Adelaide

This dissertation is submitted for the degree of

Master of Philosophy

August 2016

For Li.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Andre Scaffidi
August 2016

*

Acknowledgements

I would like to offer my sincerest thanks to the people who have helped or encouraged me in my Masters journey.

First and foremost, I would like to thank my supervisors Prof. Anthony Williams and Dr. Martin White between them providing an endless supply of knowledge, advice and providing me with some fantastic projects that I thoroughly enjoyed every bit of. I am very glad that I found supervisors that complemented my study style so well, giving me the opportunity to produce results to the best of my potential, while not feeling overwhelmed.

I would like to thank the department of physics here at the University of Adelaide for always promptly being happy to help with any inquiry or paperwork. Next, I'd like to thank the Center of Excellence for Particle Physics at the Terascale (CoEPP), for all of the opportunities to conduct work overseas or participate in workshops that have enabled me to gain skills and knowledge that have benefited me greatly and that I will continue to utilize in the future. Furthermore, thank you to the CoEPP admin staff here in Adelaide for always being friendly and welcoming as well as extremely helpful with any and all matters.

I would like to offer special thanks to Nordita as well as Stockholm university and the Oskar Klein Centre (OKC) for the hospitality and resources that allowed a majority of the muons work to be undertaken.

I would especially like to thank Chris Savage who was a major contributor to the work presented in this thesis, not only giving me the opportunity to work on some interesting and stimulating projects but for being a fantastic mentor with an encyclopedic knowledge of everything dark matter related.

Next, I would like to thank my friends and bands for just accepting that I can't make a gig/gathering/event because of something uni related. I'm really gratefully for the support and understanding, as well as your company.

Special thanks to all occupants of room 119 over the past two years. This experience has been made significantly easier having such a great group of friends to talk about everything from physics to Star Wars with. Sorry about all the foam

balls, yo-yo's and obnoxiously loud dink bottles - there are no other people I'd rather have sitting in my pockets for 5 days a week.

Lastly and most importantly, I want to thank my family. From showing me my first physics documentary, to making sure that my health is the best it can possibly be, I can't overstate the appreciation I have for the constant and unconditional source of love and support. Most of all I am thankful for what you've had to give up on my account. To Dona, thank you for always being there.

Abstract

This thesis presents advancements in two of the three avenues for the detection of particle dark matter: direct and indirect searches. The first four chapters provide an introductory overview of particle dark matter and its distribution, evidence and constraints as well as statistical tools used in direct and indirect analyses.

The second main segment of the thesis presents `LUXCalc`, a new utility for calculating likelihoods and deriving WIMP-nucleon coupling limits from the recent results of the LUX direct search dark matter experiment. After a comprehensive review of WIMP-nucleon scattering, we derive LUX limits on the spin-dependent WIMP-nucleon couplings over a broad range of WIMP masses, under standard assumptions on the relevant astrophysical parameters. We find that, under these and other common assumptions, LUX excludes the entire spin-dependent parameter space consistent with a dark matter interpretation of DAMA's anomalous signal, the first time a single experiment has been able to do so. We also revisit the case of spin-independent couplings, and demonstrate good agreement between our results and the published LUX results. Finally, we derive constraints on the parameters of an effective dark matter theory in which a spin-1 mediator interacts with a fermionic WIMP and Standard Model fermions via axial-vector couplings. A detailed section describes the use of `LUXCalc` with standard codes to place constraints on generic dark matter theories.

The final segment looks at the fact that photons can be produced from final state muons, and the consequences of considering such a process in indirect searches. Modern Monte Carlo generators and DM codes include the effects of final state radiation from muons produced in the dark matter annihilation process itself, but neglect the $\mathcal{O}(1\%)$ radiative correction that arises from the subsequent muon decay. After implementing this correction we demonstrate the effect that it can have on dark matter phenomenology by considering the case of dark matter annihilation to four muons via scalar mediator production. We first show that the AMS-02 positron excess can no longer easily be made consistent with this final state once the Fermi-LAT dwarf limits are calculated with the inclusion of radiative muon decays, and we next show that the Fermi-LAT galactic centre gamma excess can be improved

with this final state after inclusion of the same effect. We provide code and tables for the implementation of this effect in the popular dark matter code `micrOMEGAs`, providing a solution for any model producing final state muons.

Table of contents