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Steven Schramm

Searching for Dark Matter with the ATLAS Detector

Doctoral Thesis accepted by
the University of Toronto, Canada

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Supervisor's Foreword

Cosmological and astrophysical observations have determined that the density of matter in the Universe is dominated by a new form of matter that is non-luminous (Dark Matter). Although the gravitational effects of Dark Matter have been observed, the composition of this new type of matter is unknown. Therefore, one of the important open questions in particle physics, astrophysics, and cosmology is the nature and the composition of Dark Matter. Different kinds of experiments have been designed to search for Dark Matter, either directly, e.g. by recording the energy transferred to a detecting medium due to the interaction of Dark Matter with known particles, or indirectly, through the production of Dark Matter particles in high energy collisions.

This thesis was written by Dr. Steven Schramm, and it describes a search for Dark Matter particles at the Large Hadron Collider with the ATLAS experiment. The thesis focuses on the most sensitive signal for such a search where a jet of particles recoils against Dark Matter particles. Since the Dark Matter particles will almost never interact with the detector, the experimental signature features "missing momentum" from the escaping particles.

The search reported in this thesis improved on previous results on a number of fronts. First, the data were collected in 2012 from proton–proton collisions at a centre-of-mass energy of 8 TeV, which was then the highest energy ever achieved. Second, the signal sensitivity was increased by considering topologies that are dominated by one jet of particles, but that allow for additional jet activity. Third, the scope of models considered in the interpretation of the results was expanded, and a robust treatment of the validity of effective field theories was developed, allowing for better comparisons of collider experiment results with those of direct detection experiments. The search revealed no significant evidence of the production of Dark Matter particles but the ATLAS experiment improved its previous limits on the mass and production rates of these particles.

At the time of writing this foreword, the search for Dark Matter continues. The Large Hadron Collider is now producing collisions at a higher energy and new results are expected soon from the ATLAS and CMS experiments. The new and future searches for Dark Matter at the LHC will have benefited greatly from the work described in this thesis.

Toronto, Canada Prof. Pierre Savard
May 2016

Preface

The nature of DM remains one of the greatest mysteries in modern physics, despite being significantly more abundant than the normal matter with which everyone is familiar. One method to probe DM is by watching for its production in high energy collisions, such as by the ATLAS experiment at the LHC. The mono-jet search is a particularly powerful way of studying such DM production at the LHC, and is the primary focus of this thesis.

This thesis begins by considering the motivation for DM as a whole, the WIMP interpretation thereof, and existing searches for DM, as detailed in Chap. 1. The focus then shifts to the ATLAS experiment, beginning with a description of the detector in Chap. 2 and general physics object reconstruction and performance in Chap. 3. A specific focus is then placed on one of the most important performance aspects of the mono-jet analysis, jets, in Chaps. 4 and 5. The core of the mono-jet analysis is discussed in Chap. 6, while the interpretation of the analysis as a search for DM is contained in Chap. 7. The thesis ends with an outlook on the possible sensitivity of the analysis under future LHC conditions in Chap. 8 and an overall conclusion in Chap. 9.

Experimental particle physics has evolved into a field which requires very intricate detectors and complicated research questions, where no one person can contribute to every aspect of the experiment. The ATLAS Collaboration is comprised of approximately 3000 members from across the world who have all contributed. This involves building detector components, monitoring the detector operation, translating detector signals into physics information, deriving calibrations, managing the computing resources, and any number of other tasks. In reality, any individual study relies on a significant amount of work done by other people, thus the full ATLAS author list is appended to all ATLAS publications.

Similarly, this document cannot exist in isolation, as it involves both direct and indirect contributions from many individuals. Major contributions of the author within this document are listed below.

Chapter 3: ATLAS Reconstruction and Performance

The author contributed to the treatment of missing transverse momentum in ATLAS. This includes updating the reconstruction software and investigating possible cleaning criteria for the rejection of events with large amounts of fake missing transverse momentum from improperly reconstructed muons.

Chapter 4: Jet Reconstruction and Performance

The author was involved in the development and implementation of jet reconstruction software, both during Run-I activities and in preparation for Run-II. The author also contributed to the validation of jet reconstruction and associated property calculations.

The author made several small contributions to the jet calibration procedure as a whole, with a particular emphasis on corrections for jets which are not contained within the ATLAS calorimetry. The technical details of the full calibration procedure and the specific correction for non-contained jets are provided in Sects. 4.2 and 4.4 respectively.

The author was one of two principal investigators studying the impact of masked Tile calorimeter regions on the performance of jets, and was responsible for determining the optimal cleaning cut criteria. The author also wrote the associated software package for general use, and was the principal contact for the full ATLAS experiment in matters relating to jet performance around these masked regions. The technical studies that went into the creation of the cleaning selection are provided in Sect. 4.6.

Chapter 5: Jet Uncertainties

The author was the primary contact, developer, and maintainer of all aspects of the systematic uncertainties associated with the jet energy scale. This covers a large number of contributions, including (but not limited to) the creation of software tools to facilitate ease of access to the uncertainties, eigen decompositions of the uncertainties to create a more accessible format, and the creation of alternative correlation scenarios to quantify the assumptions which went into the derivation of the uncertainties. All of these concepts are thoroughly documented in this chapter.

Chapter 6: The Mono-jet Analysis

The author contributed to many different aspects of the mono-jet analysis from the start to the end of the process. The author regularly provided input and feedback on all stages of the analysis, and provided cross-checks to the main result through the independent data-driven estimation of the dominant $Z \rightarrow \nu\nu$ + jets and W $\rightarrow l\nu$ +

jets backgrounds, with a focus on the muon control regions. The author was also responsible for deriving the diboson normalization uncertainties.

In addition to these purely analysis-related contributions, the author also significantly improved performance-related aspects of the analysis. This includes optimization of the jet-related uncertainties, studies on the impact of punch-through jets, cleaning cuts for jets near masked Tile calorimeter modules, and optimization of the missing transverse momentum variation to use for the analysis.

Chapter 7: Mono-jet Dark Matter Interpretation

The author has contributed to essentially every aspect of the mono-jet Dark Matter (DM) interpretation. The author was solely responsible for the production of all of the DM signal samples, both for this analysis [1], the previous iteration of the analysis [2], and an analysis with a different but related topology [3]. This includes both the production of central values for typical analysis use and the production of samples with the variations required for the derivation of systematic uncertainties associated with the signal models. The production and validation of DM signal samples and associated systematic uncertainty derivations is provided in Appendix B due to its very technical nature.

The author was also the primary signal validation expert, contributed towards the evaluation of systematic uncertainties, and was jointly responsible for the calculation of limits for all of the DM models with an emphasis on the effective field theory samples.

The author led the ATLAS effort to understand the experimental implications of the validity of DM effective field theory models at the LHC, initially investigated for one scenario in ATL-PHYS-PUB-2014-007, fully studied in Ref. [1], and now utilized by multiple other ATLAS searches such as Refs. [3, 4]. Despite being a significant example of the author's contributions, the studies are very technical, and thus they are documented in Appendix A.

Chapter 8: Mono-jet Prospects at an Upgraded LHC

The author is one of four principal analyzers in Ref. [4], and thus was partially involved in most stages of the analysis. The author was solely responsible for the investigation of the impact of increased pileup conditions on jet performance as well as the aforementioned preliminary studies into effective field theory validity criteria. Beyond these two responsibilities, the author also contributed to the DM limit derivations for use in the sensitivity studies.

Geneva, Switzerland Steven Schramm

References

1. ATLAS Collaboration, Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, arXiv:1502.01518 [hep-ex].
2. ATLAS Collaboration, Search for New Phenomena in Monojet plus Missing Transverse Momentum Final States using 10fb^{-1} of pp Collisions at $\sqrt{s}$ =8 TeV with the ATLAS detector at the LHC, Tech. Rep. ATLAS-CONF-2012-147, CERN, Geneva, Nov, 2012.
3. ATLAS Collaboration, Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector, Eur. Phys. J. C **75** no. 2, 92 (2015), arXiv:1410.4031 [hep-ex].
4. ATLAS Collaboration, Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, arXiv:1411.1559 [hep-ex].

Abstract

Hadron colliders, such as the Large Hadron Collider (LHC), principally produce events involving hadronic activity. Such activity is typically modelled by jets, which provide a useful representation of the underlying physics. Given the ubiquity of jets in LHC events, it becomes important to ensure that their properties and performance are well understood. The full approach to jet reconstruction and calibration, as used by the ATLAS experiment, is detailed with a focus on recent improvements. The systematic uncertainties associated with jets are quantified, with the procedures and resulting reductions in uncertainties thoroughly detailed. Extra attention is placed on the treatment of high energy jets, and particularly the impact of inactive calorimeter regions and calorimeter non-containment (punch-through).

The mono-jet topology is presented as an analysis where high energy jets are particularly relevant. This search makes use of very high missing transverse momentum balanced purely by jets, enabling measurements of the production cross-section of new physics processes producing weakly interacting particles. The full Standard Model background determination is shown, and the data are seen to be consistent with the Standard Model expectations. Limits are set on the visible cross-section for new physics processes.

The results are interpreted as a search for the pair-production of Dark Matter (DM), both through Effective Field Theories (EFTs) and simplified models. Scenarios where the DM is either a scalar or fermionic particle are both considered. The validity of the EFT approach is thoroughly investigated, providing the first complete collider study into all relevant interaction types. Limits are then set on the EFT suppression scale, the WIMP-nucleon scattering cross-section, and the WIMP annihilation cross-section in order to compare with other types of DM experiments. The simplified model is used to conduct a full parameter-space scan of the mono-jet sensitivity to a wide range of conditions.

First projections for the mono-jet analysis at an upgraded LHC are presented, demonstrating the significant gain in both discovery potential and limit sensitivity that accompanies higher collision energies. The analysis is projected to double in sensitivity in the coming year, hinting at the exciting times to come.

Acknowledgments

During my doctoral studies, I had the fortune of meeting and working with a remarkable group of people. This thesis would not be the same without their support. That said, I must begin by thanking my family, and especially my parents, for their boundless patience and encouragement. I may have struggled to explain the intricacies of what I was working on, or confused them by rambling about incomprehensible topics, but they always supported and believed in me nonetheless.

Next, I wish to thank my supervisor, Pierre Savard. He gave me the freedom to pursue my own interests, yet no matter what I was doing, he could always provide valuable insight. His support enabled me to work at CERN for the majority of my degree, which was instrumental in furthering my professional development. When I set myself ambitious goals, he helped to ensure they became a reality.

I was fortunate to have the generous support of multiple benefactors during my studies. Thanks to the National Sciences and Engineering Research Council of Canada (NSERC) for repeatedly supporting my research, and the W. Garfield Weston Foundation for funding a year of my time at CERN. It is due to both of these groups that I was able to conduct the research which went into this thesis.

There are many people at the University of Toronto who helped me along the way. Thanks to Jen for all the emails and for making me look forward to the occasional Toronto visits. Thanks also to Ray and Sylvia for seeing me when I was around. Thanks to my fellow ATLAS students: Chav, Garrin, Joe, and Santiago. Special thanks go to Santiago for the fascinating discussions and the sushi, on the rare cases when we were in Toronto at the same time. Additionally, thanks to Krystyna for making bureaucracy manageable and for repeatedly helping me no matter which country I was in. The Toronto group at CERN also deserves my thanks: Lily (honorary), Nina, Nicola, Reyhaneh, and Richard.

Thanks to the jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ performance group as a whole for generally being supportive, enthusiastic, and full of people with interesting ideas. Special thanks go to Bogdan, Caterina, Cigdem, Dag, Frederik, Michael, and Pierre-Antoine for teaching me everything I know about jets. Similarly, thanks to Cate, Claire, Peter, Rosa, and TJ for teaching me about E_T^{miss}. In particular, thanks to Rosa for answering my innumerable questions, and for laying the foundation of my knowledge. Her patience at all hours of the day and night, her continual support, and her friendship are all greatly appreciated.

The exotics physics group is also full of wonderful people working on a wide range of fascinating subjects. My first and foremost thanks are to Philippe for conveying years of insight into mono-jet final states and the data-driven estimation thereof, and for always being available to cross-check anything I was doing. Thanks to my Dark friends, Johanna and Ruth, for sharing your thoughts and insights over the years as we figured out Dark Matter models together. Thanks also to Antonio and Caterina (again) for being fantastic subconvenors and for furthering the needs of the ATLAS Dark Matter community. Special thanks also go to Thomas for all of his help in understanding the validity of our Dark Matter models, and in developing techniques to properly address the concerns of the global community.

Finally, last but definitely not least, I must reiterate my thanks for Caterina (for a third time). I cannot overstate how much I have learned from her during the past years. Regardless of whether it was related to jet performance, the mono-jet analysis, Dark Matter, birds, or any other topic, she was always there at all hours of the day to help.

Contents

Acronyms

AFII	Atlas Fast simulation version II, a parametrized detector response framework
AOD	Analysis Object Data
ATLAS	A Toroidal LHC ApparatuS
BCH	Bad CHannel
BLUE	Best Linear Unbiased Estimate
BSM	Beyond the Standard Model
CL	Confidence Level
CLs	Confidence Levels statistical method for setting frequentist limits
CMB	Cosmic Microwave Background
CMS	Compact Muon Solenoid
CPV	Charge-Parity Violation
CSC	Cathode Strip Chamber
CT10NLO	A recent next to leading order parton distribution function provided by the CT (CTEQ) collaboration
CTEQ6L1	An old leading order parton distribution function provided by the CTEQ collaboration
CTEQ6M	An old leading order parton distribution function provided by the CTEQ collaboration
D3PD	Derived^3 Physics Data
DAOD	Derived Analysis Object Data
DD	Direct Detection
DESD	Derived Event Summary Data
DM	Dark Matter
ECFA	European Community for Future Accelerators
EF	Event Filter
EFT	Effective Field Theory
EM	ElectroMagnetic, usually the scale at which the raw electronic signals are used to determine the jet energy

EMB	ElectroMagnetic Barrel
EMEC	ElectroMagnetic EndCap
ESD	Event Summary Data
E_T^{miss}	Missing Transverse Momentum
FastJet	A software library for building and manipulating jets
FCal	Forward CALorimiter
Final2012	The final version of the jet calibration, uncertainties, and resolution for the 2012 dataset, released in October 2014 for the JES, with the JER still ongoing
GEANT4	GEometry ANd TRacking version 4, for the simulation of particles passing through matter
GRL	Good Runs List
GSC	Global Sequential Calibration
hadron	A bound state comprised of either two or three valence quarks held together by the strong nuclear force
HEC	Hadronic End Cap
Higgs boson	The boson associated with the Brout-Englert-Higgs mechanism and the electroweak spontaneous symmetry breaking
HL-LHC	High Luminosity Large Hadron Collider
HLT	High-Level Trigger
ID	Indirect Detection
IR	InfraRed
ISR	Initial State Radiation
JER	Jet Energy Resolution
JES	Jet Energy Scale
JVF	Jet Vertex Fraction
JVT	Jet Vertex Tagger
LAr	Liquid Argon
LC	Locally Calibrated scale, the scale at which the topo-clusters have been calibrated with a local calibration weight
lepton	Muon, electron, tau, or the anti-particles thereof. Often taus and anti-taus will not be included when discussing leptons
LHAPDF	A package and convention for the storage and access of parton distribution functions
LHC	Large Hadron Collider
LO	Leading Order
MC	Monte Carlo
MDT	Monitored Drift Tube
ME	Matrix Element
MIP	Minimally Ionizing Particle
Moriond2013	The jet calibration, uncertainties, and resolution released for 2012 data in January 2013, in time for the Moriond 2013 Conference

MSTW2008LO	An old leading order parton distribution function provided by the MSTW collaboration
MSTW2008NLO	An old next to leading order parton distribution function provided by the MSTW collaboration
MVA	MultiVariate Analysis
NCB	Non-Collision Background
NLO	Next to Leading Order
NNLL	Next to Next to Leading Logarithm
NNLO	Next to Next to Leading Order
NNPDF21LO	An old leading order parton distribution function provided by the NNPDF collaboration
NNPDF23NLO	A recent next to leading order parton distribution function provided by the NNPDF collaboration
parton	Quark or gluon
PDF	Parton Distribution Function
PDF4LHC	A working group dedicated to proper parton distribution function treatment at the LHC
pileup	Objects or energy deposits from one collision which are treated as a part of a different collision, whether in the same bunch crossing or a different one, often in the context of calorimeter jets
PMT	PhotoMultiplier Tube
QCD	Quantum ChromoDynamics, the theory of the strong nuclear interactions
RDO	Raw Digital Object
RF	Radio Frequency
RoI	Region of Interest
RPC	Resistive Plate Chamber
SCT	SemiConductor Tracker
SD	Spin-Dependent
SI	Spin-Independent
SM	Standard Model
SUSY	SUperSYmmetry
TB	TeraByte
TGC	Thin Gap Chamber
TRT	Transition Radiation Tracker
TTC	Timing, Trigger, and Control
UV	UltraViolet
VBF	Vector Boson Fusion
VEV	Vacuum Expectation Value
WIMP	Weakly Interacting Massive Particle