Searching for Dark Matter with the CMS Detector in proton-proton collisions containing a single high-$\boldsymbol{p}_{\mathbf{T}}$ photon and large $\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}$

by

Brandon Leigh Allen

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctorate of Philosophy in Physics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2019

Author . . . .
Department of Physics
May 24, 2019

Certified by . . . .
Christoph E.M. Paus
Professor
Thesis Supervisor

Accepted by . . . .
Nergis Mavalvala
Associate Department Head for Education

Searching for Dark Matter with the CMS Detector in proton-proton collisions containing a single high-p_{T} photon and large $E_{\mathrm{T}}^{\mathrm{miss}}$

by

Brandon Leigh Allen

Submitted to the Department of Physics
on May 24, 2019, in partial fulfillment of the
requirements for the degree of
Doctorate of Philosophy in Physics

Abstract

In this thesis, we present a search for dark matter in final states containing a high-p_{T} photon and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV using data collected by the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC) corresponding to an integrated luminosity of 35.9 inverse femtobarns. The main advances in experimental technique compared to previous searches in this final state are the use of data-driven control regions to constrain the main irreducible backgrounds from $Z(\rightarrow \nu\overline{\nu})+\gamma$ and $W(\rightarrow \ell\nu)+\gamma$ production and an in-depth study of the unique anomolous detector signatures that result in backgrounds due to non-collision processes. With these improvements, we have the most robust analysis of this kind presented to date.

No deviations from the predictions of the standard model are observed. The results are interpreted in the context of dark matter production and limits on new physics parameters are calculated at 95% confidence level. We focus on two simplified dark matter production models where new vector and axial mediators couple a new dark dirac fermion to the Standard Model quarks. These models are chosen as they cover a large class of WIMP-like dark matter particles that show up in many types of more complete new physics models. For the two models considered, the observed (expected) lower limits on the masses of the new mediators are 950 (1150) GeV for a dark matter particle of a mass of 1 GeV.

Thesis Supervisor: Christoph E.M. Paus
Title: Professor

Acknowledgments

This is the acknowledgements section. You should replace this with your own acknowledgements.

Contents

Chapter 1

Introduction

The Standard Model of particle physics was fully experimentally verified in 2012 with the discovery of the Higgs boson by the CMS and ATLAS collaborations at the Large Hadron Collider [**HiggsPaper**]. The Standard Model completely explains all of our observations of the microscopic wold but fails at the scale of the universe, specifically with regards to gravitational interactions. Many astrophysical observations of gravitational interactions provide strong evidence for the existence of dark matter, potentially explained by a new elementary particle not included in the Standard Model. Many experiments test the hypothesis that dark matter has a such particle physics origin including searches for the direct production of dark matter at particle colliders.

In this thesis, we focus on a recent search for dark matter in proton-proton collisions resulting in a single high-p_{T} photon and large missing transverse momentum [**Monophoton**]. First, we review the details of the Standard Model and the astrophysical evidence for dark matter. Then, we describe the Large Hadron Collider, the Compact Muon Solenoid detector, and the methods used to reconstruct the data from the collisions. Finally, we describe the analysis in detail and summarize the outlook for the future.

Chapter 2

Conclusion

In this thesis, we presented a recent search for dark matter in proton-proton collisions resulting in a single high-p_{T} photon and large missing transverse momentum. The shown analysis has the most stringent expected limits to date for this final state and provides complimentary coverage to other collider searches and searches from direct and indirect detection experiments. Figure 2-1 shows exclusion contours in the σ_{SD}–m_{DM} plane for all such analyses.

During Run 2 of the LHC, a total of $180\,\mathrm{fb}^{-1}$ of proton-proton collisions data was collected. This quintupling of the dataset size greatly reduces the statistical uncertainties inherent to the simultaneous fit methodology used in this thesis, promising further increases in discovery potential. Additionally, the larger dataset allows for new techniques and probes of more exotic models of dark matter. The coming decade should provide to be an exciting time for the study of dark matter.

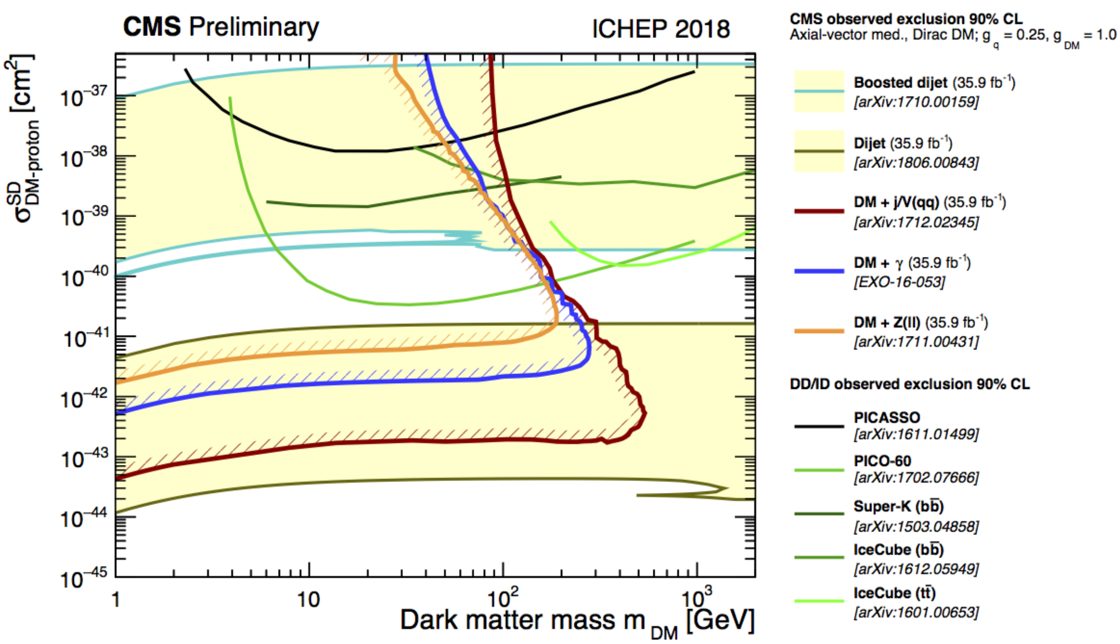

Figure 2-1: Exclusion contours in the σ_{SD}–m_{DM} plane for the latest dark matter searches. The blue contour shows the results from this thesis, while the red and orange contours show the results from similar searches with jets and vector bosons. The light yellow bands show the results from dijet searches for heavy mediators and the green contours show the results from direct and indirect detection searches. Citations for all results are given in the figure.

Bibliography

[1] *CMS luminosity measurements for the 2016 data taking period*, CMS Physics Analysis Summary CMS-PAS-LUM-17-001 (CERN, 2017).

[2] A. M. Sirunyan et al., "Search for new physics in final states with an energetic jet or a hadronically decaying w or z boson and transverse momentum imbalance at $\sqrt{s}$= 13 TeV", Phys. Rev. D **97**, 092005 (2018).

[3] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, and M. Grazzini, "Production of Drell-Yan lepton pairs in hadron collisions: Transverse-momentum resummation at next-to-next-to-leading logarithmic accuracy", Phys. Lett. **B696**, 207–213 (2011).

[4] A. Denner, S. Dittmaier, M. Hecht, and C. Pasold, "NLO QCD and electroweak corrections to W+γ production with leptonic W-boson decays", JHEP **04**, 018 (2015).

[5] A. Denner, S. Dittmaier, M. Hecht, and C. Pasold, "NLO QCD and electroweak corrections to $Z+\gamma$ production with leptonic Z-boson decays", JHEP **02**, 057 (2016).

[6] J. M. Lindert et al., "Precise predictions for $V+$ jets dark matter backgrounds", Eur. Phys. J. **C77**, 829 (2017).

[7] M. J. Ambrose et al., "A novel beam halo monitor for the CMS experiment at the LHC", JINST **10**, P11011 (2015).

[8] D. Petyt et al., *Characterization and treatment of anomalous signals in the cms electromagnetic calorimeter*, CMS Note 2010/357 (2010).

[9] D. A. Petyt et al., "Mitigation of anomalous APD signals in the CMS electromagnetic calorimeter", J. Phys.: Conf. Series **404**, 012043 (2012).

[10] K. Belasco et al., "The RooStats Project", PoS **ACAT2010**, Comments: 11 pages, 3 figures, ACAT2010 Conference Proceedings, 057 (2010).

[11] T. Junk, "Confidence level computation for combining searches with small statistics", Nucl. Instrum. Meth. A **434**, 435 (1999).

[12] A. L. Read, "Presentation of search results: the $\mathrm{cl_s}$ technique", J. Phys. G **28**, 2693 (2002).

[13] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", Eur. Phys. J. C **71**, [Erratum: 10.1140/epjc/s10052-013-2501-z], 1554 (2011).

[14] P. A. R. Ade et al., "Planck 2015 results. XIII. Cosmological parameters", Astron. Astrophys. **594**, A13 (2016).

[15] M. Backović, K. Kong, and M. McCaskey, "MadDM v.1.0: computation of dark matter relic abundance using MadGraph5", Phys. Dark Univ. **5-6**, 18 (2014).

[16] M. Aaboud et al., "Search for dark matter at $\sqrt{s} = 13$ tev in final states containing an energetic photon and large missing transverse momentum with the atlas detector", The European Physical Journal C **77**, 393 (2017).

[17] G. Busoni et al., "Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter", 2016.

[18] D. Abercrombie et al., "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum", edited by A. Boveia, C. Doglioni, S. Lowette, S. Malik, and S. Mrenna (2015).

[19] R. Agnese et al., "New results from the search for low-mass weakly interacting massive particles with the cdms low ionization threshold experiment", Phys. Rev. Lett. **116**, 071301 (2016).

[20] D. S. Akerib et al., "Results from a search for dark matter in the complete lux exposure", Phys. Rev. Lett. **118**, 021303 (2017).

[21] X. Cui et al., "Dark matter results from 54-ton-day exposure of PandaX-II experiment", Phys. Rev. Lett. **119**, 181302 (2017).

[22] E. Aprile et al., "Dark matter search results from a one Tonne $\times$ Year exposure of XENON1T", 2018.

[23] G. Angloher et al., "Results on light dark matter particles with a low-threshold CRESST-II detector", Eur. Phys. J. C **76**, 25 (2016).

[24] C. Amole et al., "Dark matter search results from the PICO−60 C3f8 bubble chamber", Phys. Rev. Lett. **118**, 251301 (2017).

[25] M. Aartsen et al., "Improved limits on dark matter annihilation in the sun with the 79-string IceCube detector and implications for supersymmetry", Journal of Cosmology and Astroparticle Physics **2016**, 022–022 (2016).

[26] E. Behnke et al., "Final results of the PICASSO dark matter search experiment", Astropart. Phys. **90**, 85 (2017).

[27] K. Choi et al., "Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande", Phys. Rev. Lett. **114**, 141301 (2015).

[28] The CMS Collaboration, *Simplified likelihood for the re-interpretation of public CMS results*, CMS Note CMS-NOTE-2017-001 (2017).