Report on the doctoral thesis

"Dark matter as a laboratory for new ideas in physics beyond the Standard Model"

by Krzysztof Jodłowski

This PhD thesis contains the study of dark matter as a laboratory for new ideas in physics beyond standard model. The key point of this thesis is to study the signatures of new physics which do not exist in the standard model, but may appear in the future experiments related to the candidates of dark matter. Those new physics may explain some tensions that exist in the laboratory experiments and in the cosmological observations. The thesis contains the original research works by the author published in the international refereed journals and also preprint and proceeding. I believe that this thesis satisfies the criteria for PhD thesis very well.

The thesis is motivated by the puzzle of dark matter and focuses on the less simplified scenarios to solve the puzzle and the signatures in the present and future experiments to test the models. This thesis covers the pre-existing results to search for dark matter and also suggest new ideas in the collider experiments, astrophysical and cosmological observations.

The thesis is composed of 9 Chapters accompanied by 5 appendices and bibliography. After the introduction in Chapter 1, basic aspects of modern cosmology and astro-particle physics related to dark matter studies are presented in Chapter 2 and 3. In Chapter 4 and 5, new experimental effects expected in the dark sector scenarios with long-lived particles are described, with particular emphasis on the relevant collider searches at the Large Hadron Collider and in the intensity frontier experiments in near future. In Chapter 6, the prospects for indirect detection of the lightest neutralino dark matter in the minimal supersymmetric standard model are discussed by taking into account the Sommerfeld enhancement effect and the formation of bound states. In Chapter 7, the indirect searches arising from the long-lived particles produced from dark matter annihilations are discussed, with its distinctive signatures from the non-local effects which have been unexplored in previous studies. In Chapter 8, the discussion is extended to the self-interacting dark matter which is produced by late decays after recombination, simultaneously solving the small-scale problems of ΛCDM model and the anomaly in the expansion of the Universe. Conclusion is given in Chapter 9, and the complementary contents are included in the appendices A to E.

In Chapter 1 "Introduction", the motivation and the contents of the thesis are summarized. Motivated by the problems of dark matter, the requirements for the scenarios beyond the standard model are reviewed. In that context, long-lived particles are introduced and searched for in different experiments. The main topics of each chapters are summarized.

In Chapter 2 "Standard Cosmological Model and the dark matter problem", the basic ingredients of the modern cosmology and the properties of dark matter are reviewed. The standard cosmology called ΛCDM model has 6 fitting parameters which are determined well by the observation of the cosmic microwave background of the Planck satellite. One of the component of ΛCDM model is the abundance of dark matter, which has the evidences of the existence also in different observations. Those include the galactic rotation curves, dynamics of the galaxy cluster, X-ray observation, Bullet cluster, CMB anisotropy, and structure formation. The identity of the dark matter is not clear yet, and only candidates are suggested. The major candidates of dark matter include the massive compact halo objects, primordial black holes, axion, wave dark matter, sterile neutrino, weakly-interacting massive particle (WIMP), and the lightest neutralino in the supersymmetric model.

In Chapter 3 "Thermal dark matter", the thermal history of dark matter and its detection methods are explained. The thermal dark matter is produced from the thermal particles in the early Universe and freeze-out. The famous example is the WIMP, whose relic density is inversely proportional to the annihilation cross section. This simple relation is modified in the case of resonant production, Sommerfeld enhancement, coannihilation, and forbidden dark matter. There is also non-thermal production of dark matter. The same interaction of dark matter is also related to the detection of dark matter. Those methods include the direct detection, indirect detection, missing energy at colliders, fixed target experiments and astrophysical probes.

In Chapter 4 "Looking for long-lived particles using secondary production", the importance of the secondary production of the long-lived particles (LLP) is investigated in the intensity frontier experiments. For this, three simplified models are used to connect the visible sector with the hidden sector through the portals such as vector, scalar, and neutrino. The experiments used to study the models with LLP include three main facilities for the intensity frontier such as FASER, MATHUSLA, and SHiP. In these setups, the secondary production of the LLP are calculated by the author in addition to the usual primary production. This new production mechanism modifies the constraints on the LLP in each model. The sensitivity for each experiments are shown in Figures 4.4, 4.5, and 4.6, for the models of dark photon with dark bremsstrahlung, inelastic dark matter, and secluded dark Higgs, respectively. As the author had found, the secondary production is important for probing the light-long lived particles, especially in the smaller lifetime regime.

In Chapter 5 "FASER as neutrino beam-dump experiment at the LHC", the secondary production of new, light particles are investigated through the interaction of neutrinos. For this, the recently approved FASERν experiment and the SND@LHC experiment at LHC are studied in the models with non-standard neutrino interactions of neutrino dipole magnetic portal and the dark gauge portal with heavy neutral leptons. The neutrinos are abundantly produced from decays of mesons originating from pp collisions at the LHC in the far-forward region. Those neutrinos interact in the detector and can produce LLPs. In models with light mediator, the production of LLPs are hugely enhanced compensating the weak interaction of neutrinos in the standard model. In the model with neutrino dipole magnetic interaction, Heavy Neutral Neutrino (HNL) is produced from the scattering of neutrino with target and soon decay into a photon and an active neutrino. In the dark gauge portal, the HNL production is enhanced through the light vector mediator and decays into dark gauge boson and a neutrino, with successive decay of dark gauge boson into electron and positron. The long-lived particles produced in the neutrino interaction with the nuclei or electrons decay in the decay vessel or inside the emulsion detector promptly. The results are shown in the Figures 5.1 and 5.4 for two models of dipole interaction and dark gauge boson, respectively.

In Chapter 6 "Testing supersymmetric dark matter in CTA", the indirect detection of weakly-interacting massive particles in the supersymmetric model is studied with regards to the gamma ray observation in Cerenkov Telescope Array (CTA). Supersymmetry is one of the most natural extension of the standard model, motivated by unification of gauge interactions at high energies, string theory, and the hierarchy problem. The lightest neutralino in the supersymmetric model with R-parity is naturally stable and become a good candidate for WIMP dark matter. The neutralino dark matter can be classified into tour types, bino, wino, higgsino, and mixed higgsino depending on its composition. The annihilation of dark matter in the galactic center produces continuum and monochromatic gamma ray signals, which can be probed by the gamma ray telescope. The author improved the study of indirect gamma rya signals in the pMSSM model focusing on the CTA. The analysis improved the projected CTA sensitivity using the state-of-the-art binned likelihood analysis, up-to-date experimental constraints and numerical tools with the Sommerfeld Enhancement in the calculations. Imposing the thermal relic density of the neutralino dark matter the new constraint is shown in Figures 6.7 and 6.8 on the plane of the dark matter mass and the annihilation cross section. In figures 6.9, the constraint is given for underabundant neutralino dark matter.

In Chapter 7 “Indirect detection of long-lived particles”, a specific model of heavy secluded WIMP dark matter is studied, which is coupled to standard model particles via the dark Higgs boson portal and dark sector species. This model contains a heavy dark matter and light new particles at the same time, and thus constrained by both the intensity frontier searches and indirect detection searches. In this model, the LLPs produced form dark matter annihilation can travel a large distance of order of kpc and generate visible signals. This new non-local effects considered in the indirect detection give distinct spectrum of visible particles compared to the previous studies. The result is emphasized in Figure 7.2. The complementarity of the non-local effects in the indirect detection of dark matter and the intensity frontier searches is well illustrated in the model of dark sector connected to the visible sector by the sub-GeV dark Higgs boson, with dark sector containing dark photon, complex scalar and dark matter. In the thesis, full analysis has been done in this model by calculating the relic density of dark matter and imposing the current and future constraints from astrophysics, cosmology and colliders. The excluded parameters are shown in the Figures 7.6 and 7.7.

In Chapter 8 “Self-interacting dark matter and the Hubble tension”, the cosmological implications of self-interacting dark matter (SIDM) and light vector mediator are studied, focusing on resolving the small scale problems of ΛCDM model and the tension in the Hubble expansion rate. The self-interaction of dark matter has been studied to solve the small scale problem and the late decay was used to affect the the Hubble expansion. Both mechanisms can be implemented in the model proposed in the thesis, where the production of the SIDM is based on late decays of a scalar particle, which freezes out from thermal plasma. The late decay of the messenger may accompany a small fraction of dark radiation production, which may affect the cosmological evolution and can improve to solve the tensions in the Hubble parameter observation. The SIDM can solve the small scale problems at the same time. Depending on the lifetime of the messenger, there are three regimes related to the problems. In the late decay regime (B), where the decay happens after BBN but before recombination with small symmetry breaking parameter, both the Hubble tension and the small scale problem can be solved. For ultra small regime (C), Hubble tension and the puzzle of the super-massive black hole (SMBH) formation may be solved. The results of the full analysis are summarized in the Figures. 8.6, 8.7, and 8.8, respectively.

In Chapter 9 “Conclusions”, the summary of the thesis is presented. The thesis investigated some of the phenomenological scenarios with long-lived particles and heavy WIMP dark matter, including the standard WIMP searches in the direct and indirect detection as well as the intensity frontier experiments. Here the importance of the long-lived particles was pointed out in the fixed target experiments and in the indirect detection of gamma-rays. For those models, the dark matter searches in the intensity frontiers are well complemented by the indirect detection and CMB observations. In some of the parameters, the production of the self-interaction dark matter from heavy particles can explain the Hubble tension and the small scale problems or the puzzle of SMBHs.

In Appendices, the complementary materials to the main text are included. The appendix A summarize the formulae used frequently in cosmology and particle physics. The appendix B lists the equations used in Chapter 4, with the $(g-2)_\mu$ contribution from A', primary and secondary production of long-lived particles and its cross sections. The appendix C complements Chapter 5 with the production of the Heavy Neutral Leptons in the neutrino interactions. The appendix D discusses formal aspects of the supersymmetry relevant to Chapter 6, and the appendix E gives the expression used in Chapter 7 such as the decay width and annihilation cross sections.

In Bibliography, 592 references are contained. The references include referenced papers to the main texts as well as the overall review papers, and the original papers by the author. They are well listed and make the thesis complete.

In summary, the thesis contains interdisciplinary subjects related to search for long-lived particles and dark matter, covering particle physics, cosmology and astrophysics. I find that Krzysztof Jodlowski has mastered these subjects and used them to understand the nature of new physics. Especially, by studying the phenomenology of the intensity frontier experiments and non-local effects in the gamma ray indirect detection, complementary and new results are obtained that were not published before. These outputs are at the level of the highest international level.

In my opinion, the submitted thesis fulfills the criteria of a very good PhD thesis. I recommend to accept it by the PhD defense committee with distinction.

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