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**Evaluation of the Ph.D. Thesis of Krzysztof Jodłowski**

To the members of the committee,

I was asked to review the thesis of Krzysztof Jodłowski, a Ph.D. student at the National Centre of Nuclear Research. I am an Associate Professor at the University of Pittsburgh. My research is in the field of theoretical particle physics, including the theory and phenomenology of dark matter (DM) and dark sectors.

Krzysztof's thesis covers a variety of theoretical and phenomenological research on DM and physics beyond the Standard Model (BSM). Krzysztof has made several significant contributions to the literature in this direction during his studies, including on long-lived particle (LLP) and light DM searches, indirect detection of SUSY neutralino DM, novel indirect detection signatures of LLPs and models addressing various anomalies in cosmology and astrophysics, and these efforts are thoroughly documented in his thesis.

A brief introduction covering the motivation behind his thesis and and overview of the various components is presented in Chapter 1. This engaging introduction indicates that Krzysztof has a good handle on the big picture questions and motivations underlying his research.

Chapter 2 presents a detailed overview of standard cosmological model and the DM problem. A clear and concise description of the Friedmann-Lematre-Robertson-Walker solution and its application to the ΛCDM cosmological model is presented. A comprehensive overview of the astrophysical and cosmological evidence for DM is then given. Finally, a survey of the possible DM candidates is presented, covering possibilities ranging from ultralight DM to composite DM and numerous options in between.

Chapter 3 provides an overview of the well motivated paradigm of thermal relic DM, or weakly interacting massive particles (WIMPs). A detailed technical survey of thermal

freezeout production is provided, including a complete treatment of the DM evolution using the Boltzmann equations. A number of variations of the basic thermal WIMP are also presented. Following this, several canonical WIMP search strategies, including direct detection, indirect detection, missing energy searches at colliders, direct production and scattering searches at accelerators, and astrophysical probes are described in detail.

Chapters 2 and 3 are well written and impressive in their scope and detail, nicely setting the stage for the later chapters covering his research projects.

Chapter 4 covers the topic of exotic LLP searches using secondary production. The chapter begins by introducing the minimal vector portal, Higgs portal, and neutrino portal models, and then discusses how DM may be incorporated into these models, including how the correct thermal relic abundance may be obtained. A detailed description of several existing or proposed experiments that are sensitive to LLPs is given, including FASER, MATHUSLA, and SHiP. The phenomenological focus is on the search potential using secondary production channels in several dark sector models wth additional states. The models under consideration and their basic properties (e.g., particle mass spectra and splittings, particle lifetimes, etc.) are presented. Following this, an overview of the modeling of production (both primary and secondary processes) and signatures (e.g., decay, scatering) is given. A summary detailing the event rate calculation is given, and then the expected experimental reach for for the models at various experiments are presented. The results are show that substantial regions of uncharted paramter space may be probed by these searches, providing further motivation for these experiments and future dedicated LLP searches.

In Chapter 5, Krzysztof discusses his proposal to employ FASER as a neutrino beam dump experiment at the LHC. The basic idea is that secondary neutrino interactions near the FASER or FASER$\nu$ detectors can probe BSM neutrino interactions with dark sector particles, such as new dipole portal couplings or new neutrino-philic force carriers. An overview of the FASER$\nu$ experiment is given, complementing the discussion of the FASER experiment presented in Chapter 4. The additional simulation components needed to model the neutrino beam and their secondary interactions are reported. The signals discussed include visible LLP decays at FASER or FASER$\nu$, as well as dark particle scattering at FASER$\nu$. A discussion of the main beam related neutrino backgrounds, along with the strategies to mitigate them, are also outlined. Much like the results presented in Chapter 4, the prospects for probing these models are quite promising, as summarized in Fig. 5.1 for the dipole portal, Figs. 5.3, 5.4 for the HNL-dark gauge boson coupling.

Chapter 6 covers a project on tests of supersymmetric DM at the Cherenkov Tele-

scope Array (CTA). It begins with a brief review of the MSSM and its neutralino sector, including the various possible neutralino annihilation modes that are important for indirect detection searches such as those at CTA. An overview of the expected distribution of dark matter in our galaxy and the calculation of the expected photon flux from DM annihilation in the galactic center is presented. The statistical method used to estimate the photon excess from DM annihilations over the background at CTA and place bounds on the annihilation cross section is discussed. To explore the prospects of CTA for neutralinos, a Bayesian scan of the pMSSM parameter space is carried out. Several publicly available tools are employed to compute the SUSY spectrum, relic abundance, annihilation cross section (including Sommerfeld enhancement), as well as sample the parameter space. The results are presented in Figs. 6.7 - 6.9, showing interesting CTA sensitivity to a variety of TeV-scale neutralinos. Two choices for the DM profile (cuspy and cored) are shown, giving a sense of the uncertainty coming from our imprecise knowledge of the dark matter distribution in the Milky Way.

Chapter 7 discusses an idea to search for long lived particles using indirect detection. The chapter explores a novel signature of heavy WIMP annihilation to a LLP, which then travels galactic distance scales before decaying to visible particles, i.e., there are non-local effects associated with the long lifetime of the annihilation products. This can be used to distinguish the scenario from standard indirect searches. The theoretical formalism for estimating and characterizing this signature is discussed, and a complex dark sector model in which this signature may be realized is presented. Other considerations include the relic density estimate, CMB probes, and intensity frontier probes, underscoring the rich variety of complementary probes relevant to this scenario.

Finally, Chapter 8 deals with a proposal to address the Hubble tension using self-Interacting dark matter. The chapter begins with a review of the Hubble tension as well as several other anomalies to be considered. The paradigm of DM self interactions is then explored and a model is presented that has the requisite features to address the various anomalies. A discussion of the thermal history and various phenomenological aspects is given. The results show that this model can improve the fit to both the $H_0$ and $S_8$ parameters and may simultaneously address some of the small scale structure problems present in the $\Lambda$CDM model.

The conclusions and a review of the results are presented in Chapter 9. Several technical appendices are also included in the thesis, supplementing the material in the main chapters.

In summary, in my view Krzysztof has produced a superb, first-rate thesis. The scope of the research is very impressive, touching on a variety of topics in particle physics model

building and phenomenology, cosmology, and astroparticle physics. Moreover, this work importantly motivates new experiments and new searches for BSM phenomena, which will help guide the community forward as we try to unravel some of the big open questions in particle physics and cosmology, such as the dark matter puzzle, the hierarchy problem, neutrino masses, etc. Krzysztof has displayed an impressive grasp of both the big picture conceptual questions and the technicalities required to do impactful phenomenological research. From my perspective, the thesis fulfills the criteria of the doctoral degree in physics, and I am requesting the candidate to be admitted to further stages of the thesis defense.

Sincerely,

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