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February 2, 2024

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Review of the PhD thesis of mgr. Théo Hugues: "Search for Dark Matter with Liquid Argon Detectors"

The PhD thesis of mgr. Théo Hugues has 157 pages, including a bibliography and a list of tables. The main contents of the thesis are two direct dark matter detection experiments using liquid argon detectors: DEAP-3600 and DarkSide-50. The two experimental analyses presented in the thesis focus on the detection of light particles in the dark sector with a mass around a few GeV or less, which requires a very low threshold for detection energies. The phenomenology of sub-GeV dark matter has been a popular topic in the field, as they are much less explored compared to their weak-scale counterpart. Also, those light dark matter scenarios may be responsible for a solution to the core-vs-cusp problem of dwarf galaxies' density profiles.

The analysis of DEAP-3600 targets a particular scenario called inelastic Boosted Dark Matter (iBDM). This scenario assumes at least four dark sector particles: One is dark matter, which does not interact with the Standard Model particles. Another is a dark photon, which is a portal between the dark sector and the Standard Model sector. The other two are dark sector particles that are lighter than dark matter. They interact with the SM particles through dark photons with tiny kinetic mixing with ordinary photons. In this scenario, a pair of dark matter particles in the galactic halo may annihilate into a pair of lighter particles in the dark sector. Due to the hierarchal mass spectrum, the produced particles are highly boosted. If such a boosted dark sector particle hits the material of DEAP-3600, it can undergo inelastic scattering and converts itself into a heavier state. This primary process, followed by a decay of the heavier state, gives rise to a unique signature with a particularly low background. The thesis describes a careful estimate of the signal yield within the iBDM scenario.

The presented analysis of DarkSide-50 is carried out in a model-independent manner, where the dark matter signal amplitude parametrises the sensitivity. The main analysis strategy is to look for annual modulation of detected events, which is expected because the relative velocity between the Earth and the dark matter halo oscillates with a one-year period due to Earth's revolution around the Sun. Interestingly, the former DAMA/LIBRA experiment claimed an observation of such an annual modulation in their data that is consistent with the dark matter signature. The relevant chapter describes a careful background estimation, advanced statistical methods, a study of the stability of the detector, and the result of the experiment.

The thesis consists of six chapters, three appendices and an extensive bibliography. After the first chapter, which is the introduction of the thesis, the second chapter provides a pedagogical review of dark matter physics. It starts with the description of the comprehensive evidence for dark matter, which covers galaxies' rotation curves, puzzles in galaxy clusters, the cosmic microwave background and the Big Bang Nucleosynthesis. In the next section (section 2.2), several ideas for solutions to these problems are discussed. This includes modified gravity, massive astronomical compact halo objects (MACHOs), primordial black holes, sterile neutrinos, QCD axions and axions-like-particles. On top of these, particular attention is paid to the weakly interacting massive particles (WIMPs) as a dark matter candidate. The WIMP miracle paradigm has been explained together with the "freeze out" mechanism and the relation to models beyond the Standard Model, such as the weak scale supersymmetry. Section 2.3 is devoted to the experimental detection of dark matter. Three avenues are discussed, which are (i) direct production of dark matter particles at particle accelerators, (ii) indirect detection and (iii) direct detection. The direct detection is the main subject of this thesis.

Chapter 3 describes the basics of liquid argon detectors for direct dark matter detection experiments. Section 3.1 explains the details of scintillation processes in liquid argon when a particle X scatters with an argon atom. It also touches upon the importance of underground argon to suppress the contamination of cosmologically activated radioactive isotopes. In section 3.2, the DarkSide-50 detector is explained. Each detector component, as well as the geometry and the detector design, are described in detail. The concept of Slow Control parameters is also introduced. Section 3.3 describes the DEAP-3600 detector. In addition to the detector geometry and design, the separation between electron and nuclear recoils is demonstrated in Fig. 3.6.

Chapters 4 and 5 contain the main findings of the thesis. Chapter 4 presents an analysis of DEAP-3600 to look for a signature predicted by the inelastic Boosted Dark Matter (iBDM) model. The first two sections (sections 4.1 and 4.2) describe the overall concept of the model and its signature in the DEAP-3600. It is argued that the signal becomes optimal for DEAP-3600 when the dark matter mass is in the sub-GeV range. Four reference model points are introduced and the energy spectrum of the primary process, $\chi_1 T \to \chi_2 T$, is calculated and presented in Fig. 4.2 for each reference point. The excited state, χ_2, produced in the primary process is expected to decay inside DEAL-3600. The energy spectrum of this secondary process is also calculated and shown in Fig. 4.4 for each reference point. The following section (section 4.3) is devoted to the estimation of DEAL-3600's sensitivity to the iBDM model. Within this section, the lifetimes of χ_2 and the dark photon, X, have been discussed as it is important to know whether the secondary process can be resolved from the first one. One of the most important results of the thesis is presented in Fig. 4.9, 4.10 and 4.11, where the expected reaches are presented on the plane of the dark photon mass and the kinetic mixing parameter, ϵ, for given m_{χ_1}, γ_1 and m_{χ_2} parameters. It is demonstrated that world-leading sensitivity can be achieved on the dark photon parameter plane with just one year of the DEAP-3600 data. A summary of this chapter is given in section 4.4.

Chapter 5 is devoted to the annual modulation analysis for low-mass dark matter with DarkSide-50. Section 5.1 explains the general idea of the annual modulation of dark matter signature. Section 5.2 describes the low-mass dark matter signature. It also identifies the dominant background from the decay of radioactive isotopes. The formulae for the event rate and the chi-square analysis are laid down. The next section (5.3) introduces the Lomb–Scargle periodogram method, which is used to detect a frequency spectrum in the data. Section 5.4 studies the stability of the DarkSide-50 detector, which is important because the time variation of the detector performance may produce a false modulation signal. The Slow Control parameters play an important role in this analysis. The list of all 71 Slow Control parameters is shown in Table 5.3, with their correlation to the signal yield in each Region of Interest (RoI). The result of the analysis is presented in section 5.5. After validating the data with Monte Carlo simulation, the limit is set on the dark matter signal amplitude, which is shown in Fig. 5.44. The result is also interpreted in the simplified WIMP scenario, and the limit is set on the dark matter mass vs the spin-independent cross-section plane, shown in Fig. 5.46. These two plots are considered to be one of the main findings of the thesis. In fact, the obtained limit provides the strongest limit in the world for the dark matter mass below 3 GeV.

Finally, Chapter 6 provides a short conclusion of the thesis.

Overall, the thesis of mgr. Théo Hugues is well written, and the descriptions are clear for the most part. The thesis presents two main findings. One is the sensitivity of DEAP-3600 on the iBDM model, shown in Figs. 4.9-4.11. This demonstrates that DEAP-3600 is capable of probing the unexplored region of the dark photon parameter space. The other is the result of DarkSide-50 analysis dedicated to low-mass dark matter. The exclusion plot, shown in Fig. 5.46, exhibits the world's strongest limit on the dark matter mass vs the dark matter-nucleon spin-independent cross-section in the low mass region below 3 GeV. These results are original and have significant scientific value and impact.

While the quality of the thesis certainly meets the standard, there are, in my opinion, a number of places where the thesis can be improved. There are typographic mistakes in various places. To mention just a few, "to be consider" $\Rightarrow$ "to be considered" on page 5 and "Argo" $\Rightarrow$ "'Argon' on page 33. The structure of chapters can be better organised. For example, in Chapter 4, I would put the lifetime estimate and the energy spectrum calculation in section 4.2 instead of 4.3 because the reference model points, the secondary process and the energy spectra of primary and secondary processes are discussed there. The quality of plots and figure captions can be improved. In many plots, e.g. in Figs. 4.15 and 4.16, the axis labels and the legend fonts are too small and sometimes unreadable. Some plots do not show the unit of the axes, e.g. in Fig. 4.16. In Fig. 4.7, PE probably represents the number of photoelectrons. In Fig. 4.6, the x-axis label shows “Primary Energy [PE]”. Does the PE here represent a unit of energy? In the plots shown in Figs. 4.9-4.11, there are coloured regions that are excluded by other experiments. However, no explanation is provided other than the references. A short description of these regions should be provided as it is important to compare the present result with the former one. What assumptions are made for those coloured regions? How do they compare with the assumptions in the present analysis?

Apart from those minor points, the contents of the thesis are rich and well-described. A comprehensive review of dark matter in Chapter 2 shows the author’s firm theoretical basis. The detailed descriptions of the signal reactions, background estimations, and statistical analyses also reflect the author’s deep understanding of the experiments and capability to perform scientific works independently.

Summing up, I consider the doctoral thesis of Théo Hugues to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to public defence.

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