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## **Plan B for particle physics: finding long lived particles at CERN**

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### **Citation**

Bondarenko, K. (2018, November 15). *Plan B for particle physics: finding long lived particles at CERN*. *Casimir PhD Series*. Retrieved from <https://hdl.handle.net/1887/67089>

Version: Not Applicable (or Unknown)

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**Note:** To cite this publication please use the final published version (if applicable).

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**Issue Date:** 2018-11-15

# Summary

The recent success of the Standard Model has culminated in the confirmation of one of its most important predictions – the discovery of the Higgs boson. However the search for the new particles has not ended. The observed but unexplained phenomena in particle physics and cosmology (such as neutrino masses and oscillations, dark matter and baryon asymmetry of the Universe) indicate that new particles may exist beyond the Standard Model. Despite this, these particles have so far evaded our detection. One potential reason for this is because they could be too heavy to be created by accelerators, and hence constructing larger accelerators in order to cross the *Energy Frontier* is now seen as a primary focus for particle physics.

Alternatively, some of the hypothetical particles can be sufficiently light (lighter than the Higgs or  $W$ -boson), to interact with particles from the the Standard Model but even weaker than neutrinos do. In order to explore the possibility of super-light particles, the science community is also focussing their attention on experiments at the *Intensity Frontier*. Such experiments aim to create high-intensity particle beams and use large detectors to search for rare interactions of hypothetical ‘feebly-interacting particles’. In addition to experiments that are already running, a number of new projects have been proposed in recent years in order to search for light and feebly interacting particles in accelerator facilities throughout the world. Recognizing the importance of exploring the Intensity Frontier, the CERN Management created, in 2016, a dedicated Study Group “Physics Beyond Colliders” that analyses the potential of non-LHC searches for new particles at CERN.

In this thesis we have explored the prospects of two proposed experiments at CERN, both with the primary aim to search for new particles beyond the Standard Model. The first is the – *Search for Hidden Particles* or *SHiP* –, which is a fixed-target experiment that uses the proton beam of the Super Proton Synchrotron (SPS). The second experiment is – MATHUSLA (*MAssive Timing Hodoscope for Ultra Stable neutraL pArticles*) – a surface detector proposed to sit alongside the ATLAS or CMS experiment. Both experiments are sensitive to similar regions of parameter space and therefore it is important to assess their scientific possibilities in a consistent and objective manner.

In this work we have concentrated on several well-motivated extensions of the Standard Model, such as *heavy neutral leptons* (neutrino-like Majorana fermions,

feebly interacting and with GeV-scale mass) and a *Higgs-like singlet scalar*. These particles can be directly responsible for some of the Beyond Standard Model phenomena or can serve as *portals* connecting the Standard Model to the particles that provide solutions for the observed phenomena.

For both extensions we have reviewed and revised the phenomenology of their production and detection, taking into account the direct requirements of the experiments in question, something that previous studies had not done. Our results are directly suitable for sensitivity studies of particle physics experiments (ranging from proton beam-dump to the LHC) aiming at searches for portal particles. In particular, they are being used by the SHiP collaboration for the official sensitivity studies.

We have used detailed Monte-Carlo simulations of both production and decay, complemented by background studies in order to estimate the experimental reach. We have extended the official software framework of the SHiP experiment – FairSHiP, implementing our new findings for the heavy neutral leptons to include the scalar production and detection of a singlet scalar in SHiP. The resulting sensitivity curves have been included into two official papers of the SHiP collaboration.

The new half-analytical approach allowed us to calculate more accurately the sensitivity reach of the SHiP experiment and compare it to that of MATHUSLA in a consistent manner under an identical set of assumptions. In addition, we have proposed a new and effective way to scan over the 4-dimensional parameter space of the heavy neutral leptons in order to identify sensitivity regions for arbitrary couplings. Such a feature was requested by many research groups and is crucial if we are to answer the question: *What models of leptogenesis can be directly probed at particle physics experiments?*

Finally, we have also examined the extension to SHiP known as iSHIP. While originally designed to study the properties of  $\tau$ -neutrinos, iSHIP is an extra detector that is suitable for detecting light dark matter particles – members of the “dark sector” produced via the scalar portal.

In May 2020 the next European Strategy for Particle Physics will be formulated. The question of the next-generation Intensity Frontier experiment will be a part of its scientific agenda. Regardless of which new Intensity Frontier experiment will be approved, the results of this project will be used by many theory groups as well as by experimental collaborations, by the experts of the European Strategy for Particle Physics, etc. In addition, the SHiP collaboration is currently preparing its *Comprehensive Design Report* — an official document that finalizes the design of the experiment. The results of this thesis are part of that effort.