Search for heavy sterile neutrinos with SHiP

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Abstract
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The keV range sterile neutrino is a cornerstone in the $\nu$MSM $^{[1-3]}$ which is one of the models that will be explored by the Search for Hidden Particles (SHiP) experiment. The $\nu$MSM is a low-scale seesaw model which is based on introducing three right-handed sterile neutrinos, also referred to as Heavy Neutral Leptons. It assumes masses for the sterile neutrinos which are similar to those in the quark and charged lepton sector. The keV range sterile neutrino provides a decaying form of dark matter. The other two sterile neutrino are in the GeV range allowing them to produce the expected pattern of neutrino flavor oscillations and masses, and allowing them to generate baryon asymmetry of the Universe via leptogenesis. In order to guarantee sufficient production of keV sterile neutrinos at around temperatures of 100 MeV in the Universe, the heavier sterile neutrinos are required to produce a large lepton asymmetry which survives down to these temperatures. This allows making a natural connection in the $\nu$MSM between the GeV masses for the two heavier sterile neutrinos and the constraints on the keV DM sterile neutrino. In these respects the $\nu$MSM is one of the most economical extensions of the Standard Model which simultaneously allows accounting for neutrino masses and oscillations, baryogenesis, and dark matter.

In the $\nu$MSM the sterile-active neutrino mixing leads to production of the heavier sterile neutrinos in weak decays of hadrons, making them accessible in an accelerator based experiment. The same mixing gives rise to decays to SM particles. As a consequence of the small mixing angles allowed in the $\nu$MSM and the interesting mass range, the lifetimes are in the order microseconds to milliseconds. For the keV sterile neutrinos, the upper limit on the Yukawa coupling means that its production is completely negligible in an accelerator based experiment.

More generally, the $\nu$MSM is part of a large class of models $^{[4]}$ with portals to a Hidden Sector which addresses the shortcomings of the Standard Model including inflation, the hierarchy problem etc, without involving a new scale. Instead they are based on introducing very weakly interacting particles such as Majorana leptons, dark photons, dark scalars or axion-like particles (ALPs) with masses below the electroweak scale. Even in the scenarios in which BSM physics is related to high mass scales such as SUSY, many models contain degrees of freedom with suppressed couplings that stay relevant at much lower energies. For example, in the extensively studied MSSM, the existence of light neutralinos and some other light SUSY particles has not been excluded. Motivated by dark matter phenomenology, hidden sectors have also been introduced in weak-scale supersymmetric models with gauge mediated or gravity mediated SUSY breaking. If the SUSY breaking feeds into the hidden sector only via some suppressed mechanism such as gauge kinetic mixing, a GeV scale mass spectrum for the hidden sector may be dynamically generated $^{[5,6]}$.

Given the small couplings and mixings, and hence typically long lifetimes, the hidden particles have not been significantly constrained by previous experiments, and the reach at current experiments is limited by both luminosity and acceptance. The strongest bounds on the interaction strength of new light particles exist up to the mass of the kaon.
Above this scale the bounds weaken significantly. SHiP is a new type of intensity frontier experiment motivated by the possibility of searching for any type of hidden particles with masses from sub-GeV up to $\mathcal{O}(10)$ GeV with super weak couplings down to $10^{-10}$. Consequently, SHiP has also a complementary sensitive to a part of the SUSY low-energy parameter space.

As with the GeV range sterile neutrino, many of the hidden particles in the same mass range are produced in the decays of heavy hadrons. In addition, the coupling of the dark photons and the ALPs to gauge bosons means that they may also be produced through photons: dark photons from proton bremsstrahlung, electromagnetic decays of mesons, as well as through direct QCD production, and ALPs through Primakoff production.

The key experimental parameters in the phenomenology of the Hidden Sector models are relatively similar. This allows a common optimization of the design of the experimental facility and of the SHiP detector (Figure 1). Since the hidden particles are expected to be predominantly accessible through the decays of heavy hadrons and photon interactions, the facility is designed to maximize their production and the detector acceptance while providing the cleanest possible environment. The proposal locates the SHiP experiment on a new beam extraction line which branches off from the CERN SPS transfer line to the North Area. The high intensity of the 400 GeV beam and the unique operational mode of the SPS provide ideal conditions. The current design of the experimental facility and
the estimates of the physics sensitivities assume the SPS accelerator in its present state. Sharing the SPS beam time with the other SPS fixed target experiments and the LHC allows producing $2 \times 10^{20}$ protons on target in five years of nominal operation. In order to maximize charm and beauty production, and the production and interactions of photons, while minimizing the neutrino background from pions and kaons, the choice of the target material is driven by the requirement of high atomic mass number, high atomic number, and short interaction length. Currently the target is a hybrid design of a molybdenum alloy and pure tungsten. As a result, with $2 \times 10^{20}$ protons on target, the expected yields of different hidden particles greatly exceed those of any other existing or planned facility in decays of both charm and beauty hadrons.

The target is followed by a hadron stopper and an active muon shield which deflects the high flux of muon background away from the detector. The detector for the hidden particles is designed to fully reconstruct their exclusive decays and to reject the background down to below 0.1 events in $2 \times 10^{20}$ protons on target. The detector consists of a large magnetic spectrometer located downstream of a 50m long and 5m × 10m wide decay volume. In order to suppress the background from neutrinos interacting in the fiducial volume, it is maintained under vacuum. The spectrometer is designed to accurately reconstruct the decay vertex, the mass, and the impact parameter of the decaying particle at the target. A set of calorimeters and muon chambers provide identification of electrons, photons and muons, and pions. A dedicated high resolution timing detector measures the coincidence of the decay products which allows rejecting combinatorial backgrounds. The decay volume is surrounded by background taggers to veto neutrino and muon inelastic scattering in the surrounding structures which may produce long-lived SM $V^0$ particles, such as $K_L$ etc.

![Figure 2: Sensitivity to the heavier sterile neutrino (HNL) as function of the mass in the scenario with inverted mass hierarchy for the active neutrinos and Yukawa couplings with electron flavour dominance][8]
With $2 \times 10^{30}$ protons on target, the experiment is able to achieve sensitivities which are up to four orders of magnitude better than previous searches. As shown in Figure 2 for sterile neutrinos below the mass of the D-meson, SHiP can probe the cosmologically interesting region of parameters and approach the lower limit in couplings, determined by the neutrino oscillations. Such an experiment would clearly be an essential complement to the searches for Dark Matter in astroparticle physics experiments and for new physics in accelerator based experiments.

References


