INSTITUTO SUPERIOR TÉCNICO

PROJECTO MEFT

Optimization of the Selection of Exotic Particles in the SHiP Experiment

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1 Introduction

Since the Ancient Greece that humanity has been concerned with understanding the fundamental blocks of all existing matter. Throughout the 20^{th} century a specific branch dedicated to studying this phenomena was developed, *particle physics*.

One of the biggest achievements of this branch was to develop the most successful model so far through the use of *Quantum Field Theory* as the mathematical basis: the Standard Model, which contains all the known elementary particles. The last one to be discovered was the Higgs boson, which was found in 2012 at both CMS [1] and ATLAS [2], and completed the search for all the predicted Standard Model particles.

Aside from predicting the elementary particles of our universe, the model also describes these particles' interactions with each other through the electromagnetic, weak and strong forces, and its simplified equation, Eq. (1), contains all this information.

$$\mathcal{L}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\overline{\psi}\not{D}\psi + \left(\psi_i y_{ij}\psi_j\Phi + \text{H.c.}\right) + |D_\mu\Phi|^2 - V\left(\Phi\right) + \mathcal{L}_{QCD} \tag{1}$$

Even though Eq. (1) might seem simple at first, every interaction between fermions and bosons is duly accounted for, and ever since 2012, and the discovery of the Higgs boson, all accelerator experiments should be explained by this model.

It just so happens that so far, the predictions have no significant deviations from the experimental results obtained, apart from a few cases which haven't reached a consensus yet [3], and the model seems to be self consistent up to very high energy scale.

1.1 Shortcomings of the Standard Model

Although most of the Standard Model predictions have very slight deviations from the experimental results, there are some clear fundamental problems that cannot be explained by the vanilla model.

Some of these are the baryon asymmetry of the universe (BAU), the existence of dark matter and both the neutrino masses and oscillations between these particles.

As such, as of now, the objective is to find particles and interactions that extend beyond the Standard Model, thus making these be known as *beyond the Standard Model* (BSM) problems.

The way in which these searches are being made is mostly by increasing the energy of the accelerators, where we assume that the new particles are heavier than the ones we can currently create, and thus, we need to increase the center of mass energy of the collisions ($\sqrt{s}$), such as the LHC.

However, there might be another reason as to why we can't see new physics: the interactions with these BSM particles may be too feeble in order for us to detect them. This means that we need to increase both the luminosity and the precision of our experiments.

In this latter case the BSM particles may not interact directly with the SM, thus being located in *hidden sectors* that are only accessible through some specific portals, such as vectors and neutrinos.

1.2 Useful Portals

From the previously mentioned possibilities, there are 2 of major interest. The most straightforward of both is the vector portal, where one hypothesis is to have a kinetically mixed field usually denoted as **Dark Photon**. The second one, which is slightly more complex is the **Neutrino Portal**.

1.2.1 Dark Photon

In this case, the portal is an additional field A'_μ with field strength $F'_{\mu\nu}$ that acts in a similar fashion to the SM photon, with whom it kinetically mixes with.

This A'_μ is associated with a U′(1) symmetry that exists in the hidden sector and as such is usually known as **Dark Photon**.

Due to this association, it couples to the hypercharge field $F_Y^{\mu\nu}$ with a mixing angle of $\varepsilon << 1$, and also to the BSM particles charged under U′(1), χ, with coupling g'.

Since we are now dealing with particles that aren't accounted for in the SM, the Lagrangian presented in eq. (1) is no longer fully correct, and a few extensions need to be made.

The previous remarks then lead to the new Lagrangian presented in Eq. (2) [4].

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'^{\,2}_{\mu\nu} + \overline{\chi}\left[\gamma^\mu\left(i\partial_\mu - g'A'_\mu\right) - m\chi\right]\chi - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\,2}_\mu \tag{2}$$

Aside from being able to provide a simple extension of the SM without charging any of the existing fields under the new gauge group, the existence of the Dark Photon is able to provide an explanation to the anomaly in the muon magnetic moment, with a simple one loop correction.

Due to this problem minimal models without any particles charged under the new group have been excluded [5], which makes it so that the discovery of dark photons would guarantee the existence of a hidden sector with a plethora of dark matter candidates.

Not only that, but it also guarantees that these candidates can be light (in the MeV range) and have the possibility of self-annihilation, which in the right conditions would satisfy both the necessary amount of dark matter in the universe, as well as explain the excess of positrons in the galactic bulge [6].

Apart from all of this, the hypothesis of coexistence between dark photons and Heavy Neutral Leptons (HNL) is also entertained.

Due to the nature of the dark photons, there are 3 main sources of production for these: meson decays into pairs of a SM photon and a dark photon, bremsstrahlung production in quasi-elastic scatterings between protons and nucleons, and lastly QCD production via quark anti-quark annihilation and quark gluon interactions producing quarks and dark photons, which are the predominant processes for heavy dark photons.

1.2.2 Neutrino Portal and Heavy Neutral Leptons

In 1962 a model with oscillating neutrinos was proposed in order to explain mass differences between the electron and the muon, while unifying these [7]. After the discovery of the tau neutrino (ν_τ), we got the current model in which the 3 flavoured neutrinos are superpositions of the mass eigenstates ($\nu_{1,2,3}$), yielding the relation in Eq. (3), where $\mathbf{U}_{\text{PMNS}}$ is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathbf{U}_{\text{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \tag{3}$$

Associated with this superposition, we have that the probability of a neutrino with flavour α transitioning into one with flavour β over a distance L, with energy E is given by Eq. (4) [8], with $\mathbf{U}$ being read as $\mathbf{U}_{\text{PMNS}}$:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \delta_{\alpha\beta} - 4\sum_{j>i}\mathbf{U}_{\alpha i}\mathbf{U}^*_{\beta i}\mathbf{U}^*_{\alpha j}\mathbf{U}_{\beta j}sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) \tag{4}$$

Even though this model is very successful, it isn't able to solve all of the problems found within neutrino physics.

Along the runs of MiniBooNE and LSND, data that significantly differed from the 3 neutrino flavour oscillation model was found [9].

One of the solutions to this problem is the introduction of additional neutrinos, being that we can easily generalize Eq. (3) and Eq. (4). However, since there are only 3 neutrinos that interact weakly [10] (in the force sense), the extra ones must be sterile neutrinos, also known as heavy neutral leptons (HNL).

This means that the only way for us to interact with said sterile neutrinos is through the oscillations, and as such we have a neutrino portal. If we denote L_α as the left lepton doublet, N_I as the sterile neutrinos, $\widetilde{\Phi}$ as the Higgs boson and $F_{\alpha I}$ as a Yukawa coupling, then only right-chiral components of N_I couple to the SM and this leads to adding a generalized neutrino lagrangian term given by Eq. (5). Notice that we consider the new particles to be Majorana ones.

$$\mathcal{L} = \mathcal{L}_{SM} + \left(F_{\alpha I} \left(\overline{L}_\alpha \cdot \widetilde{\Phi} \right) N_I + \frac{M_I}{2} \overline{N}_I^C N_I + H.c. \right) \tag{5}$$

This leads to couplings to the HNLs (I index) given by $\mathbf{U}_{\alpha I}^2 = \frac{v^2 |F_{\alpha I}|^2}{M_I^2}$, with some variables defined in Eq. (5), $\alpha = e, \mu, \tau$, and v the vacuum expectation value of the Higgs boson.

Although simple models of (3+1) neutrinos can solve this problem, due to the factor Δm_{ij}^2 in the transition probability, the possible phase space for the BSM particles becomes much wider when we consider models with $N \geq 2$.

Not only do these models offer explanations for the neutrino oscillations, but they also provide good candidates for dark matter, as well as possible explanations for the matter anti-matter asymmetry [11].

A very important idea to take from the latter section is that in order to interact with BSM particles and further detect them there is either a suppression by a factor of ε^2, in the case of the Dark Photons, or we are dealing with neutrino like particles, which are known for their feeble interaction rates.

This means that we need enough luminosity to allow the BSM particles to be created, and also specific detectors that make possible for these to decay into SM ones that we can interact with, and as such detect. The Search for Hidden Particles experiment is one such that will push the boundaries on these constraints.

1.3 The SHiP Experiment

The SHiP experiment [12, 13] is planned to be a fixed target multi-purpose experiment that focuses on the detection of several BSM particles, as well as the study of tau neutrino (ν_τ) physics and lepton flavour violating processes.

Both the target and beam featured will be of protons, where the latter is expected to yield a total amount of 2×10^{20} protons, with a momentum of 400 GeV/c, along the experiment's operational time.

The goal of the collisions is to generate charm and beauty hadrons, which decay quickly, hopefully through the desired branchings. However, due to the nature of particle physics, there will also be a big production of background pions and kaons, which in turn might decay into undesired muons and neutrinos, which must be removed as early as possible.

Due to its 0 background nature, the goal is to have beam-induced background reduced to 0.1 events over the lifetime of the experiment, which leads to the need of having 2 shields immediately after the target.

Firs off, there is a hadron stopper and afterwards there is a muon shield. The hadron stopper is made of heavy metals, and is also magnetized, in order to start helping deflect the muons. The muon shield is composed by two magnetic sets that generate intense fields, being that the only muons that enter the detector acceptance are ones that underwent large-angle multiple scattering, and weren't deflected enough in the first set, getting refocused by the second. This fraction however is very small compared to the original sample (10^{-6}).

After the shields there are the several detector apparatuses. These can be divided into the Scattering and Neutrino Detector (SND) and the Hidden Sector Spectrometer (HSS), leading to something close to the schematic presented in Fig. 1.

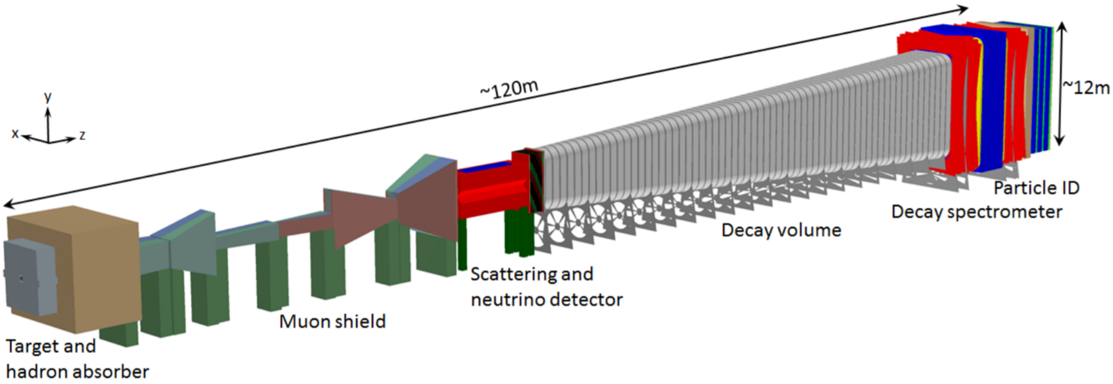

FIGURE 1: Overview of the SHiP experiment taken from [13]

1.3.1 Scattering and Neutrino Detector

As of now, the plan is to have the SND made of a magnet, an emulsion target interwoven with target trackers, followed up by 3 downstream trackers and a final simple muon identification system.

Although the magnet is standard procedure in detectors, in this case special care is taken to avoid affecting all of the stray muons deflected by the initial muon shield.

The combination of the emulsion target and target trackers is able to detect τ leptons by disentangling the production and decay vessels, and can even detect light dark matter by tracking the scattering of nucleons and electrons throughout the absorber planes, as well as showers of the latter. Besides this, charmed hadrons can also be studied extensively. The first target tracker also acts as a veto for charged particles entering the detector.

The downstream trackers are also target trackers. However, in this case they have no emulsion targets in between, and as such are there in order to measure the momentum and charge of long tracks.

The muon identification system not only identifies muons previously produced in the emulsion tracker, but also doubles down by identifying any possible last minute neutrino interactions, before the beam enters the decay vessel.

1.3.2 Hidden Sector or Decay Spectrometer

The DS has the vacuum vessel, a surrounding background tagger, a spectrometer straw tracker paired with a magnet, a timing detector, an electromagnetic calorimeter and at last a downstream muon system.

The surrounding background tagger detects charged particles that either enter the vessel or are produced in interactions between neutrinos and the vessel's walls, thus reducing the background.

The spectrometer straw tracker is able to measure track parameters of charged particles with enough accuracy to reconstruct vertices corresponding to HS particles. Here the timing detector is utilized in order to veto any possible combinatorial background.

The electromagnetic calorimeter is present in order to detect γ decays and also improve electron and hadron separation.

At last, there is a muon identification system, that not only provides the expected muon identification, but can also be utilized in order to further reduce the combinatorial background.

1.3.3 Dark Photon and HNL production mechanisms

In the SHiP experiment, the HNL will be produced in a very standardized manner. Since they only couple to neutrinos, they will be produced in leptonic decays of D and B mesons, which in turn are created in the target, upon collision of the beam.

Although the dark photons may seem more complicated on a surface level since they have 3 production modes, all of them are produced at the target. Both the bremsstrahlung and QCD productions at the target are very self-explanatory. The meson decays however are slightly less trivial.

Although beauty and charm charged mesons decay almost instantly, the same isn't true for kaons, which have longer lifetimes. However, since there is a meson shield the kaons are stopped prematurely, and as such there is no need to consider dislocated production vertices. This leads us to consider that dark photons produced from these processes are created on the target.

2 Particles of Interest and Focus of the Thesis

As of now, the SHiP experiment is still under preparation, and since the research subject and plausible BSM theories presented are too wide, my thesis will for now focus on optimizing the selection of **Dark Photons** created through kinetic mixing, and **Heavy Neutral Leptons**.

More specifically, the work will revolve around easily traceable leptonic decays of the dark photons, and the decays of the HNL to leptons accompanied by Pi and Rho mesons.

As such, the decays presented in Eq. (6) will take the spotlight.

$$\begin{aligned} A' &\rightarrow e^- e^+ \\ A' &\rightarrow \mu^- \mu^+ \\ A' &\rightarrow \tau^- \tau^+ \\ N &\rightarrow e^- \pi^+ \\ N &\rightarrow e^- \rho^+ \\ N &\rightarrow \mu^- \pi^+ \\ N &\rightarrow \mu^- \rho^+ \end{aligned} \tag{6}$$

Since this is a zero background experiment, the study and rejection of background noise will also be performed. Here preference will be given to muon and neutrino backgrounds coming from the target, with special interest on the neutrinos that can lead to processes similar to those of particles of the hidden sector, and possibly cosmic rays.

3 State of the Art

3.1 Dark Photons

Concerning the dark photon, as mentioned previously, models with no charged particles under the new U(1) have been excluded.

Apart from this, the only experimental data that we have on dark photons sums up to the exclusion region. In Fig. 2 we can see the current state of dark photon research, as well as the phase space of the mixing angle ε versus the mass of the particle, m_{DP} or $m_{A'}$, that will possibly be explorer at SHiP.

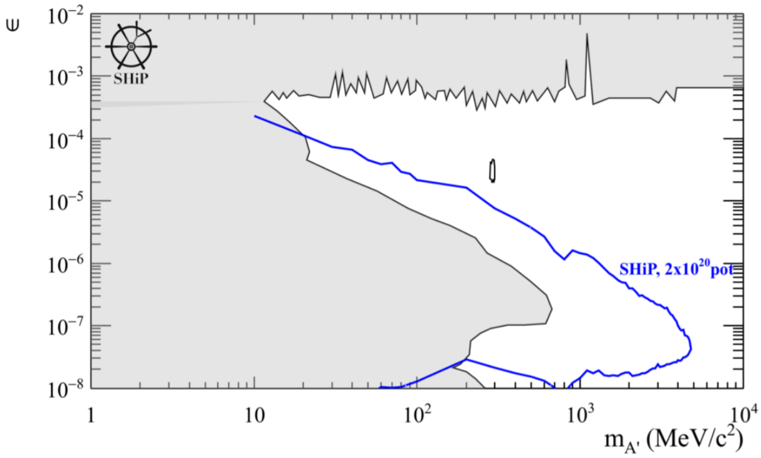

FIGURE 2: State of the rejected phase space for dark photons in the minimal model with particles charged under the new U(1) and the possible SHiP phase space search region taken from [13].

As for the cross section contributions of all 3 production modes, as well as the decay branching ratios, as a function of the dark photons' mass, we have the predictions given by Fig. 3. Note that from $m_{DP} = 0.6\text{GeV}/c^2$ onward the branching ratios for $e^- + e^+$ and $\mu^- + \mu^+$ are approximately equal, and the same would be verified for $\tau^- + \tau^+$ if we reached an appropriate energy level, since the dark photon behaves similarly to a SM photon, and in the SM there is no lepton flavour violation. In order to see a monte-carlo simulation with a clearer distinction between these branching ratios, one can go to [14].

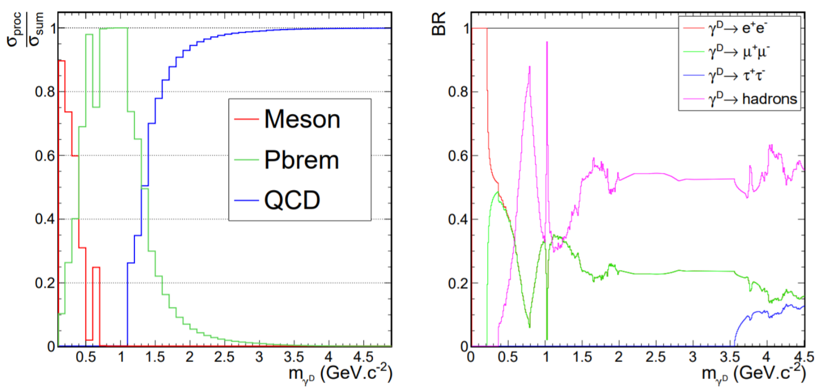

FIGURE 3: Predictions made about the contribution of the dark photons' production mode to the total cross section, and decay branching ratios, respectively, taken from [13].

3.2 Heavy Neutral Leptons

As of now, extensions of the SM with one HNL have been discarded as effective ones [8], and as such we are mostly looking at (3+2) models. Another very sought after model category is the (3+3) neutrinos, where the third HNL acts as dark matter, with an even more reduced coupling to the SM neutrinos, and as such isn't crucial in explaining either the oscillations nor BAU.

So far, the (3+2) minimal heavy neutral lepton model (νMSM) is still coherent with the experimental measurements, and will be utilized as the base-line.

Since HNL are yet to be experimentally found, there is still only a excluded region of the $|\mathbf{U}_\mu|^2$ vs m_N based on previous experiments, which can be seen in Fig. 4. $|\mathbf{U}_\mu|^2$ is the coupling of the muon neutrino to the HNL.

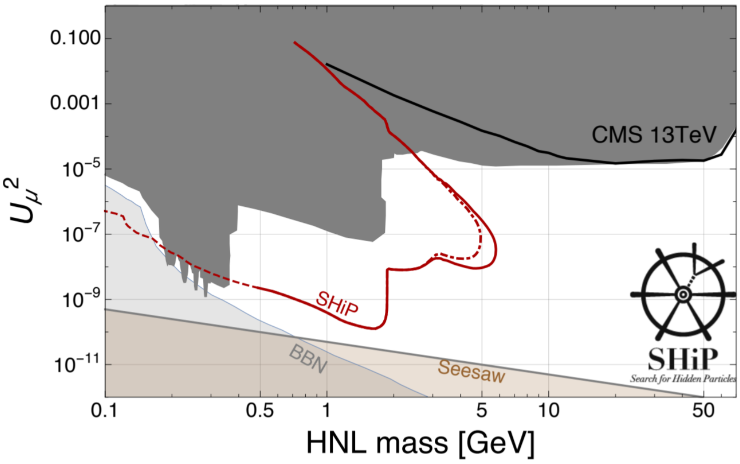

FIGURE 4: State of the rejected phase space for HNL in the νMSM and the possible SHiP phase space search region taken from [15]. The dashed line corresponds to simulations with no charmed open beauty mesons, while the solid one has a production rate comparable to that of at the LHC energies.

According to the most recent estimations [13, 15], the following branching ratios of the open charm and beauty meson decays into HNL are expected to be the following, when only $|\mathbf{U}_e|^2 \neq 0$, which is the case that generates higher mass HNL:

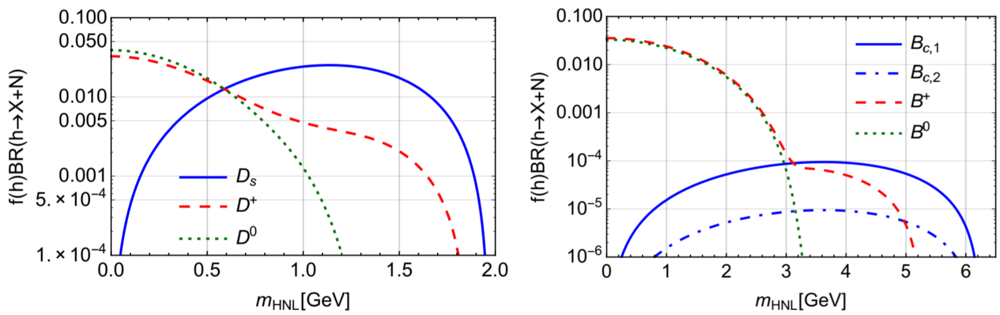

FIGURE 5: Expected branching fractions of the open charm and beauty mesons into HNL, through electron mixing only, taken from [15]

In a similar vein, the branching ratios of the HNL according to a model where the couplings $|\mathbf{U}_\alpha|^2$ are all equal, with α = e, μ or τ, are expected to be given according to Fig. 6.

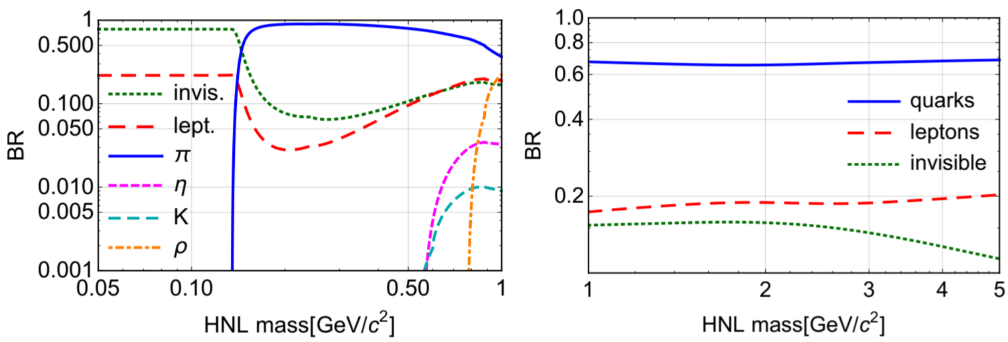

FIGURE 6: Expected decay products from the HNL produced at SHiP, taken from [13]

This leads to the HNL possible phase space search at the SHiP experiment being given by Fig. 7.

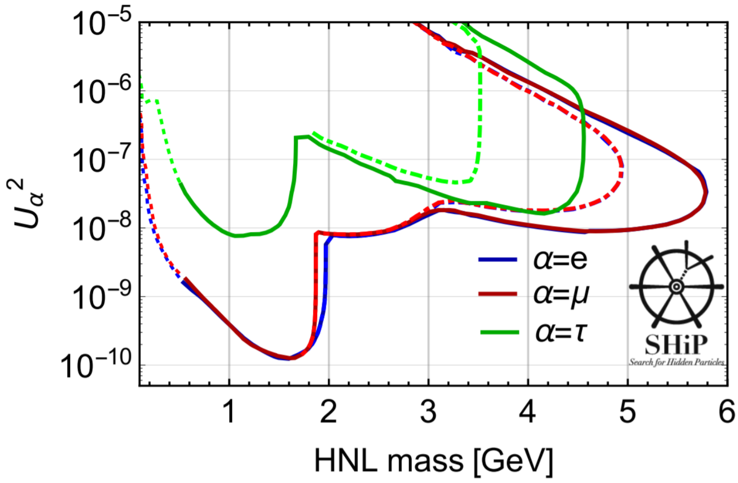

FIGURE 7: HNL accessible phase space in the SHiP experiment, where the dashed line doesn't account for B_C mesons, and the solid one accounts for a fraction similar to the one found at LHC energies, taken from [15]

4 Workplan

All of the work will be performed utilizing the FairSHiP software, based on FairROOT [16]. In here, the original proton-proton on-target collisions are simulated using Pythia8, and the following propagation and interaction of particles is done through GEANT4. Neutrinos' interactions are done through GENIE, and both heavy flavour production and muon deep inelastic scattering are done resorting to Pythia6 and GEANT4.

In the HNL production cascades are taken into account, unlike for the Dark Photons, where no such thing is done.

At the end of the simulation, the interaction of the products with the detector is done through GEANT4.

If we interpolate the relevant data presented in the figures in Section 3 with the desired decays in Eq. 6, we obtain the following mass (M) thresholds in the phase space for the Dark Photons in Table 1 and HNL simulations in Table 2, within the parameters given by Fig. 2 and Fig. 7, for the DP and HNL respectively.

Notice that in Fig. 2 the limits of sensitivity of the SHiP experiment are implied. These generalized limits are $0.002 < m_{DP} < 4.1\ GeV/c^2$ and $1.64 \times 10^{-9} < \varepsilon < 1.64 \times 10^{-3}$.

It is relevant to notice from Table 2 that the effective simulations of HNL decaying to pions plus leptons will only happen for masses superior to $0.4\ GeV/c^2$, since lower masses aren't relevant.

Production$^{(1)}$/Decay$^{(2)}$ Mode	**M_{min} (GeV/c^2)**	**M_{max} (GeV/c^2)**
Meson$^{(1)}$	-	0.7
P bremsstrahlung$^{(1)}$	-	2.0
QCD$^{(1)}$	1.1	-
$e^- + e^{+\ (2)}$	-	-
$\mu^- + \mu^{+\ (2)}$	0.25	-
$\tau^- + \tau^{+\ (2)}$	3.5	-

TABLE 1: DP simulation mass thresholds. When not explicitly mentioned, the limits are the ones in Fig. 2.

Production$^{(1)}$/Decay Mode$^{(2)}$	M_{min} (GeV/c^2)	M_{max} (GeV/c^2)
charmed mesons$^{(1)}$	0.4	2.00*
beauty mesons$^{(1)}$	0.4	-
$\pi + l$ $^{(2)}$	0.14	-
$\rho + l$ $^{(2)}$	0.80	-

TABLE 2: HNL simulation mass threshold. When not explicitly mentioned, the limits are the ones in Fig. 7. *For more detail on this limit see [13], page 56, Fig. 65, which shows $f_{q \to M} \times Br_{M \to HNL+X} / U^2$ as a function of the HNL mass.

After all the relevant data as been simulated, we will try to find patterns among the decay products that allow us to distinguish these decays from background noise, and as such, optimize the amount of true positives, which are expected to be very few, since both Fig. 2 and Fig. 4 consider regions where more than 2.3 hits are expected along the experiment's lifetime.

Since the neutrinos generated on the collisions can perform deep inelastic scattering with nucleons in the vacuum vessel volume, background events similar to those generated by some HS particles may emerge, such as unstable uncharged mesons.

Given this a set of neutrinos, previously generated in the target, will be propagated through this volume. From the resulting set of data, the relevant decay products, which mimic possible HS particle decays, will be analyzed. This is mostly due to unstable uncharged Kaons.

Even though the decay vessel is set to be under vacuum (1 mbar), further studies in which the pressure is higher might be done, since if we can prove that the detector can still maintain the lesser than 0.1 background events detected, without compromising the rate of true positives, we can lower the vacuum requirements of the experiment, which is still to be built.

Since the SHiP experiment is still being projected, a few alterations to the detectors' configurations may be made, and as such simulations that account for these changes might have to be made, mostly due to the variation in the background signals.

5 Timeline

The following plan of action for the thesis shows an ideal progression of the work. Due to the uncertainty of the experimental apparatuses and the inexperience in working on long projects such as these, as well as their natural volatility, reviews of the plan will be performed on a regular basis, and as such this is by no means definitive, and acts mostly as a guideline.

- **March - May, 2019**: General study on the multiple purposes of the SHiP experiment and introduction to the FairSHiP software which will be crucial along the project.
- **May - July, 2019**: Running of all the simulations within the useful phase-space presented in Section 4.
- **July - August, 2019**: In-depth understanding of the kinematics involved in the decays presented in Eq. (6), as well as those of the decays of unstable neutral mesons which might be produced in deep-inelastic interactions between neutrinos and nucleons.
- **September - November, 2019**: Analysis of the relevant kinematic variables along the simulated spectrum and application of cuts within the acceptance range that provide a comfortable confidence level.
- **December, 2019 - March, 2020**: Buffer time which in the worst case scenario will be needed to finish the previously established work. If the work goes at least as expected, this time will be

utilized in order to further the research. This might be done by applying machine learning to the previously performed analysis. Other hypothesis are to study the hadronic decays of the DP, or more difficult to detect decays of the HNL. Similar studies to those presented here might also be done in the scalar sector, and on Axion Like Particles.

- **March - May, 2020**: Slot of time reserved to finalize the work and polish some unfinished business, and end up writing the thesis. The first draft should be ready in mid May in order to allow for timely alterations. The final delivery should be at the end of May, and the dissertation should be done in early June.

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