EVALUATION OF THE MUON COMBINATORIAL BACKGROUND AT SHiP EXPERIMENT

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Declaration of Authorship

I, Stavros KITSIOS, declare that this thesis titled, “EVALUATION OF THE MUON COMBINATORIAL BACKGROUND AT SHiP EXPERIMENT” and the work presented in it are my own. I confirm that:

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- I have acknowledged all main sources of help.

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Signed: 

Date: 
“Nothing lasts...But nothing is lost...”
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Dedicated to my Family and C.Z.
The main subject of this thesis is the evaluation of the muon combinatorial background at SHiP (Search for Hidden Particles) collaboration experiment. The goal is to give an estimate of the number of events we expect in the detector which are considered to be the dangerous background. In the first chapter there is a general introduction of the Standard Model and. There is also a reference for the neutrinos and their masses. The fact that oscillations have been observed regarding their flavor change, it means that the have mass. The forth family of neutrinos, the Heavy Neutral Leptons, is introduced in the second chapter including the Seesaw Mechanism Type-I and the $\nu$MSM. The Seesaw Mechanism is a possible scenario of how neutrinos obtain mass. The $\nu$MSM is based on the Seesaw formulation and introduces the right-handed chiral neutrinos. The third chapter is dedicated to the description of the SHiP experiment. Physics performance is also included as well as information regarding the setup. Muon background sources are mentioned in the forth chapter such as neutrino background, deep inelastic scattering (DIS), cosmic muon background and also the HNL signal for the channel $HNL \rightarrow \pi \mu$. The last chapter is dedicated to the muon combinatorial background where a detailed analysis is present for the estimate of the background.
Chapter 1

Introduction

1.1 Standard Model

The objective of particle physics is to understand the basic structure and laws in nature. The Standard Model (SM) was the name given around 1970 to a theory of fundamental particles and how they interact with each other in order to give an interpretation to what we observe as structure in nature. It has united everything that was known about the subatomic particles at the time and it also managed to predict the existence of additional particles. There are seventeen particles in the SM. [9] The Higgs boson which was discovered in 2012 is the only scalar boson we know so far in nature. By the term scalar we mean that its spin is zero. Higgs bosons are excited states of the Higgs field which is a scalar field. In other words, it has a constant value everywhere in space and as a consequence it is coordinate-independent in space. On the other hand, a vector field changes its value from point to point such as the gravitational or the magnetic field. All the masses of the fundamental particles are obtained by the interaction with the Higgs field.

In nature, we know four fundamental forces so far, the gravitational, the electromagnetic, the weak and the strong. The electromagnetic force manifests itself through the forces between charges involving the exchange of photons and its range is infinite. The strong force is the force which is developed between quarks by exchanging gluons. Its range is very small, $10^{-15}$ meters and it is the strongest of all the forces. The force tends to increase while quarks fend off each other. The electroweak force involves the exchange of the intermediate vector bosons, W and Z. Since the mass of those particles is on the order of 80 GeV, the uncertainty principle dictates a range of $10^{-18}$ meters which is about 0.1% of the diameter of the proton. Finally, the fourth force is the gravitational force with an intermediate carrier which is considered to be the graviton. It has not been observed yet and it is supposed to be massless due to the unlimited range of the gravitational force. [9]

Fundamental particles are either the building blocks of matter, called fermions, or the mediators of interactions, called bosons. There are twelve named fermions and twelve bosons in the SM. Every elementary particle has an intrinsic quantum number which is the spin.
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Fermions have half integral spin quantum number \( \frac{1}{2} \), and bosons have integral spin, \( 1, 2, 3, \ldots \). The Planck constant \( \hbar \) is a physical constant and it is the Planck constant with units \( \text{eV} \cdot \text{s} \). No other values are allowed between these because spin is a quantised quantity.

The force carriers of the SM (eight gluons, photons (\( \gamma \)), \( W^\pm \) and \( Z^0 \)), the bosons, have spin 1 since they go with vector fields. The Higgs boson corresponds to a scalar field so it has spin 0 as it has already been mentioned.

Fermions are divided into two groups of six. Those that must bind together are called quarks and those that can exist independently are called leptons. Quarks are always bound into triplets or doublets. They come in three flavours, red, green, blue and their anti-“color”. Triplets are called baryons and doublets are called mesons. For instance, a proton and a neutron are composed by three quarks and mesons such as \( \pi \) are composed by two quarks, one quark and one antiquark, \( q\bar{q} \). The other six fermions are called leptons and they are the light particles of the SM. Although, tau lepton (\( \tau \)) broke this rule because it is found to be almost two times heavier than the proton. [9]

\[ \begin{align*}
\text{up} & : \text{u} \\
\text{charm} & : \text{c} \\
\text{top} & : \text{t} \\
\text{down} & : \text{d} \\
\text{strange} & : \text{s} \\
\text{bottom} & : \text{b} \\
\text{electron} & : \text{e} \\
\text{muon} & : \text{\( \mu \)} \\
\text{tau} & : \text{\( \tau \)} \\
\text{electron neutrino} & : \nu_e \\
\text{muon neutrino} & : \nu_\mu \\
\text{tau neutrino} & : \nu_\tau \\
\end{align*} \]

**Figure 1.1:** Standard Model of particle Physics.

[18]

1.1.1 Neutrinos in the SM and their masses

The neutrinos are a subgroup within the leptons. They are separated in three flavors. The electron, muon and tau are matched with the electron neutrino, muon neutrino and tau neutrino respectively (\( \nu_e, \nu_\mu, \nu_\tau \)). In the past, neutrinos were considered to be massless but currently we know they have very small mass and they interact very
weakly with the rest of the particles thus making it very difficult to detect them. The neutrino can interact via both interaction types of weak force, charged current (CC) and neutral current (NC) interactions. The CC interaction is mediated by the massive $W^\pm$ and NC by the $Z^0$. The large masses introduce a large suppression factor into the cross section, making the neutrino an "invisible" particle with the ability to travel through extremely large quantities of matter with no detectable interactions taking place.

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{neutrino_interactions.png}
\caption{Left: Charge current interaction. Right: Neutral current interaction. [4]}
\end{figure}

The fact that neutrinos have mass can be understood via neutrino oscillations. It is a quantum mechanical effect where a neutrino is created with a specific lepton flavor ($e$, $\mu$, $\tau$) and later, it can be measured to have a different flavour. The probability to measure a particular flavour for a neutrino changes as it propagates through space. First it was predicted by Bruno Pontecorvo in 1957 and neutrino oscillations have since been observed by experiments in different contexts each time. As mentioned in the previous section, SM contains three generations of flavours of neutrinos labeled according to the charged leptons with which they partner in the weak interactions. These three eigenstates of the weak interaction form a complete orthogonal basis. One can construct a basis out of three neutrino states of definite mass, $\nu_1$, $\nu_2$, $\nu_3$, which diagonalize the neutrino’s free-particle Hamiltonian. Each flavor state can then be written as a superposition of mass eigenstates, and vice-versa. The mixing matrix has been suggested by Pontecorvo, Maki, Nakagawa, Sakata and it is known as PMNS matrix. It is a unitary matrix and is described by:
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\[ U = \begin{pmatrix} U_{e1} & U_{e1} & U_{e3} \\ U_{e1} & U_{e1} & U_{e1} \\ U_{e1} & U_{e1} & U_{e1} \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} + s_{13}s_{23}c_{12}e^{-i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{-i\delta} & s_{23}c_{12} - s_{13}s_{23}s_{12}e^{-i\delta} \\ s_{23}c_{12} - s_{13}s_{23}c_{12}e^{-i\delta} & -s_{23}c_{12} - s_{13}s_{23}s_{12}e^{-i\delta} & c_{13}s_{23} \end{pmatrix} \] (1.1)

\[ \sin \theta_{ij} = s_{ij}, \cos \theta_{ij} = c_{ij} \text{ and } \delta \text{ describes the Majorana CP violating phase. Its unitarity implies that the kinetic term in the lagrangian is diagonal in both cases. If we assume a three flavour oscillation, the mixing between flavours and masses is given by:} \]

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \] (1.3)

\[ P(\nu_\alpha \rightarrow \nu_\beta) = 1 - 4 \sum_{i>j} Re(U_{ai}^* U_{bi} U_{aj} U_{bj}) \sin(\Delta m^2_{ij} L / 4E) + \sum_{i>j} Im(U_{ai}^* U_{bi} U_{aj}^* U_{bj} \sin(\Delta m^2_{ij} L / 2E)) \] (1.4)

[7] The vector on the left of equation 1.3 represents a neutrino state expressed in the flavour basis, and on the right is the PMNS matrix multiplied by a vector representing the same neutrino state in the mass basis. A neutrino of a given flavour \( \alpha \) is thus a “mixed” state of neutrinos with different mass. If one could measure directly that neutrino’s mass, it would be found to have mass \( m_i \) with probability \( |U_{ai}|^2 \). Currently our knowledge about neutrino mass hierarchy is shown in figure ?? below:

In the SM, it is assumed that neutrinos have zero masses but we have already said that they have mass but it is very small. Furthermore, there is no right-handed component of the \( \Psi \) field. According to the Higgs mechanism, by adding three right-handed neutrino fields in the Lagrangian we end up with a mass relation:

\[ m_\nu = \frac{y_\nu \langle 0 | H | 0 \rangle}{\sqrt{2}} \] (1.5)

[8] where \( \nu = \langle 0 | H | 0 \rangle \) is the expectation value of the Higgs field in the vacuum and \( y_\nu \) is the Yukawa coupling constant of the Higgs field. We see that we cannot extract any valuable information out of
this in order to explain the small value of the neutrino mass. In general, when a fermion interacts with the Higgs field its right-handed component turns into a left-handed and vice-versa. Neutrinos do not have a right-handed component and also we can see that from 1.5 the expectation value of the Higgs field is 174 GeV in vacuum and the Yukawa coupling $y^e_\nu$ cannot acquire values small enough in order to get a reasonable value for the neutrino mass.

At this point, it is remarkable to mention that Seesaw mechanism which is based on the Majorana theory, could give a reasonable explanation to this issue. The basic idea of this model is the new definition of a right-handed component of the field in relation with the left-handed and it is given by $\Psi_R = C \bar{\Psi}_L^T$ [15] where C is the charge conjugate operator. Since the right-handed component has been defined, by taking the conjugate of the Majorana field we have:

$$\Psi^C = (\Psi_L + \Psi_L^C)^C = \Psi_L^C + \Psi_L = \Psi$$

(1.6)

[14] We conclude from 1.6 that the charge conjugate field is the same as the field itself. In other words, a particle is its own antiparticle and it should be neutral. Now if we try to express the mass eigenstates in the approximation of two flavour oscillations corresponding to two massive fields $\nu_1$ and $\nu_2$ we get:

$$\nu_1 \approx (\nu_L + \nu_L^C) - \frac{m_D}{m_R^2}(\nu_R + \nu_R^C)$$

(1.7)
\[ \nu_2 \approx (\nu_R + \nu_R^c) - \frac{m_D}{m_R^2} (\nu_L + \nu_L^c) \]

where \( m_D \) is the Dirac mass and is of the order of 1 MeV and \( m_R \) is the mass term of the right-handed component of the field. It is implied that the mass of the neutrino will be of the order of \( 10^{-3} \) MeV.

This introduction was an overview of the Standard Model and the current knowledge of what we know now about the neutrino masses. In the next chapters we will refer to the Seesaw-Type I mechanism and neutrino Minimal Standard Model (νMSM) as well as the SHiP collaboration experiment (Search for Hidden Particles) where new horizons are to be opened up regarding the nature of neutrinos. We are going to introduce a fourth family of neutrinos, the Heavy Neutral Leptons (HNLs), and describe the experiment which will probably contribute to a new discovery.
Chapter 2

Neutrino Masses

2.1 Heavy Neutral Leptons

So far, the Standard Model of elementary particles has provided a robust concept of how particles interact with each other. However, it is not a complete theory since it is impossible to explain some phenomena we have observed in nature. These are the so-called "beyond Standard Model" phenomena. For instance, neutrino masses and their oscillations as we mentioned in the previous chapter, cannot be explained with the SM. Also, another interesting topic is the very small difference (order of $10^{-11}$) between matter and antimatter and this is the Baryon Asymmetry of the Universe (BAU). Dark matter and what it consists of is not known either. "Energy frontier" experiments have taken place like LHC, at CERN in order to investigate new physics according to the heavier mass of new particles. There is another possibility of research which does not lie in the heavy mass of the particles but at the intensity frontier due to their "weak" interactions with matter. Now, we introduce three new leptons called Heavy Neutral Leptons. HNLs are a new family of leptons which do not interact with any of the fundamental forces except from the gravitational one. Their mass seems to be very large in comparison with other active neutrinos. If they are light neutrinos, their observation can be achieved via accelerator experiments or an indirect observation via CP-violation processes. Theory claims the existence of three heavy neutral leptons. If there is only one, then one of the active neutrinos gets mass. If there are two, two of the active neutrinos get mass and for the case of three, every active neutrino has a mass. There are six new CP-violation phases, the BAU can be understood and the concept of dark matter could be explained precisely.

In the SM, the basic reasons that neutrinos do not have a mass is that there is no right-handed field component. Consequently, neutrinos cannot have a Dirac mass and also we refer to a renormalizable theory according to quantum field theory which means that interactions take place within the dimension boundary to be $\leq 4$. If $m_\nu \neq 0$, all the arguments above collapse. So if those new particles are heavier than $m_W$ which is the electroweak mass scale, we can parametrize them at low energies with an effective lagrangian. A more robust description of the effect is presented in the next section.
2.1.1 Seesaw Type-I for one generation

The Lagrangian for a free fermion is given by:

\[ L = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi = i\bar{\Psi}\gamma^\mu \partial_\mu \Psi - m\bar{\Psi}\Psi \]

(2.1)

[5]

The Dirac equation obtained from Euler-Lagrange relations is

\[ (i\gamma^\mu \partial_\mu - m)\Psi = 0 \]

(2.2)

[5]

By decomposing the field into two components, left and right, we have \( \Psi = \Psi_R + \Psi_L \) and we can easily see that the Dirac mass term becomes

\[ m\bar{\Psi}\Psi = m\bar{\Psi}_L\Psi_R + m\bar{\Psi}_R\Psi_L \]

(2.3)

Then the Lagrangian in 2.1 becomes:

\[ L = \bar{\Psi}_R(i\gamma^\mu \partial_\mu - m\Psi_L)\Psi_R + \bar{\Psi}_L(i\gamma^\mu \partial_\mu - m\Psi_R)\Psi_R \]

(2.4)

Again from Euler-Lagrange relations we get two Dirac equations with respect to the left and right-handed component of the field according to 2.3:

\[ i\gamma^\mu \partial_\mu \Psi_L = m\Psi_R \]

(2.5)

[5] and

\[ i\gamma^\mu \partial_\mu \Psi_R = m\Psi_L \]

(2.6)

[5] Notice that according to SM if we set the masses equal to zero we get the Weyl equations. However, instead of doing that, we will define the right-handed component of the \( \Psi \) field in terms of the left-handed, so:

\[ \Psi_R = C\Psi^T_L \]

(2.7)

[5] and we end up with relation 1.6.

Now if we write down all the mass terms (Dirac and Majorana terms) included in the Lagrangian we get:
\[ L_{\text{mass}} = L_L^L + L_D^R + L_M^R + L_D^L = \]
\[ = \frac{1}{2} m_L \bar{\nu}_L \nu_L + m_D \bar{\nu}_R \nu_L + \frac{1}{2} m_R \bar{\nu}_R \nu_R + m_D \bar{\nu}_L \nu_R \rightarrow \]
\[ \rightarrow L_{\text{mass}} = (\bar{\nu}_L^C \nu_R) \left( \begin{array}{cc} m_L & m_D \\ m_D & m_R \end{array} \right) \left( \begin{array}{c} \nu_L^C \\ \nu_R^C \end{array} \right), \]
\[ M = \left( \begin{array}{cc} m_L & m_D \\ m_D & m_R \end{array} \right) \]
\[ \text{(2.11)} \]

is a the mass matrix. The terms \( m_D \) and \( m_{L,R} \) are the Dirac mass term and the the masses of left and right component respectively. In 2.11, the term which describes the Dirac mass is responsible of the fact that the fields are not eigenstates of the masses. So, we are looking for a diagonal matrix:

\[ M' = \left( \begin{array}{cc} m_1 & 0 \\ 0 & m_2 \end{array} \right) \]
\[ \text{(2.12)} \]

\( m_1 \) and \( m_2 \) are the definite masses of the neutrinos. As a consequence, we are looking for a 2 × 2 PMNS matrix in order to be able to satisfy the condition:

\[ \left( \begin{array}{c} \nu_L \\ \nu_R^C \end{array} \right) = U \left( \begin{array}{c} \nu_{1,L} \\ \nu_{2,L} \end{array} \right) \Rightarrow U M U = M' \]
\[ \text{(2.13)} \]

The matrix which could satisfy the above condition is the simple unitary matrix \( U = \left( \begin{array}{cc} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{array} \right) \). Now relation 2.13 becomes:

\[ \left( \begin{array}{c} \nu_L \\ \nu_R^C \end{array} \right) = \left( \begin{array}{cc} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{array} \right) \left( \begin{array}{c} \nu_{1,L} \\ \nu_{2,L} \end{array} \right) \Rightarrow \]
\[ \Rightarrow \left\{ \begin{array}{l} \nu_L = \nu_{1,L} \cos \theta - \sin \theta \nu_{2,L} \\ \nu_R^C = \nu_{1,L} \sin \theta + \cos \theta \nu_{2,L} \end{array} \right. \]
\[ \text{(2.15)} \]

and we can extract the mass eigenstates for this particular case and we have:

\[ \left\{ \begin{array}{l} m_1 = \frac{1}{2} (m_R + m_L + \sqrt{(m_R - m_L)^2 + 4m_D^2}) \\ m_2 = \frac{1}{2} (m_R + m_L - \sqrt{(m_R - m_L)^2 + 4m_D^2}) \end{array} \right. \]
\[ \text{(2.16)} \]

Assuming that \( m_\nu = m_L = 0 \) and \( m_R >> m_D \), it turns out that:
\[ \begin{align*}
m_1 &= \frac{m_D}{m_R} \\
m_2 &\approx m_R \quad \Rightarrow m_1 = \frac{m_D^2}{m_2}
\end{align*} \quad (2.17) \]

[14] From 2.17, Dirac mass is on the order of 1MeV and the mass of the heavy partner is \( \approx 10^{15} GeV \). So, it is implied that the mass of the neutrino would be on the order of \( \sim 10^{-3} eV \).

![Diagram](image)

**Figure 2.2:** The splitting of Dirac neutrino in a right-handed and left-handed component.

[14]

### 2.1.2 Seesaw Type-I formulation for two generations

The Seesaw mechanism can be expanded for the case of two neutrino mixing. The Majorana and Dirac masses are now described by mass matrices.

\[ M_R = \begin{pmatrix} Y & 0 \\ 0 & X \end{pmatrix} \quad (2.18) \]

[6]

and

\[ M_D = \begin{pmatrix} e & b \\ f & c \end{pmatrix} \quad (2.19) \]

[6]

The elements of Eq. 2.18 describe the masses of the right-handed neutrino states and the elements of Eq. 2.19 give the masses of the left-handed neutrino states. Coupling between the elements of 2.19 and 2.18 takes place. For instance, an element of the Dirac mass matrix \((e, b, f, c)\) describes a Dirac mass coupling \(\nu_L\) to a particular \(\nu_R\). The formulation proceeds in the same way as for the case of one neutrino in section 2.1.1 but we will not go through any further details. Similarly, the case of three neutrinos follows the same concept but then we have \(3 \times 3\) mass matrices.

This was an overview of how neutrinos obtain mass according to Seesaw-Type I mechanism. Next, we will refer to another approach which is the \(\nu\) Minimal Standard Model.
2.1.3 Neutrino Minimal Standard Model ($\nu$ MSM)

As in the previous section, we also add three right-handed neutrinos which are described by the three additional right-handed massive fields. The gauge group remains unchanged as well as the fermion families and there is no introduction of a new energy scale. To begin with it has been verified by many experiments that neutrinos should have a mass since we have found two mass scales, $\Delta m^2_{\text{atm}}$ and $\Delta m^2_{\odot}$.

It requires the existence of two or more right-handed neutrinos. In general, the $\nu$ MSM shall be able to explain the concept of dark matter, the neutrino oscillations, the baryon asymmetry of the universe (BAU). We have already mentioned that the mass scale should be equal or smaller than the electroweak scale so we can replace the $\tilde{\Phi}$ which is the Higgs doublet by the Higgs expectation value in vacuum which is $\nu = 174 \text{ GeV}$. The Lagrangian then becomes:

$$L = L_{SM} + i \bar{\nu}_{R,I} \gamma^\mu \partial_\mu \nu_{R,I} - (m_D)_{\alpha I} \bar{\nu}_{L,\alpha} \nu_{R,I} - (m_D)^*_{\alpha I} \bar{\nu}_{R,I} \nu_{L,\alpha} - \frac{1}{2} ((M_M)_{IJ} \bar{\nu}^C_{R,I} \nu_{R,J} + (M_M^*)_{IJ} \bar{\nu}_{R,I} \nu^C_{R,J})$$

(2.20)

with $m_D = \langle 0 | H | 0 \rangle F$ and $M_M$ is the Majorana masses. In the previous section we have shown that small Dirac mass requires large Majorana mass.

Some of the most important aspects of $\nu$ MSM is the Baryon Asymmetry of the Universe and Dark Matter (DM). A sterile neutrino preferably the lightest one, could be a candidate for warm DM. It is not known so far what the structure of DM is, even though it covers the $25\%$ of the total matter in the universe.

Considering the lightest HNL as a DM candidate, its Yukawa coupling to the Higgs is very small ($10^{-12}$)[1] and as a consequence its contribution to the $\nu$MSM is negligible. In other words, the mass matrix does not include mixing of the light HNL with the active neutrinos. The fact that it could be a DM candidate means that its lifetime should be larger than the age of the universe and its mixing angle should be:
There are two possible decays of the light HNL. Either to three neutrinos or to one neutrino and a photon. Below you can see the Feynmann diagrams for each case.

![Feynman diagrams](image)

**Figure 2.4:** Decay of HNL in three neutrinos(Left). Subdominant decay of HNL in one neutrino and one photon(Right).[1]

The right Feynman diagram in 2.4 has a decay width which is very small and this is reason that this type of decay is the subdominant. The width is given by:

$$\Gamma_{\nu \gamma} = \frac{9\alpha G_F^2 U^2 M_N^2}{256\pi^4} = \frac{5.55 \times 10^{-30} \text{sec}^{-1}}{3.66 \times 10^{-48} \text{keV}} \times \left[ \frac{U^2}{10^{-8}} \right] \left[ \frac{M_N}{1 \text{keV}} \right]^5$$

(2.22)

We can see the large lifetime of the DM candidate HNL from Eq. 2.22 since the decay width $\Gamma_{\nu \gamma}$ is related to the lifetime with the relation:

$$\Gamma \propto \frac{1}{\tau}$$

(2.23)

where $\tau$ is the lifetime.

Since we have said that the lightest HNL is a possible candidate of DM, we are left with two HNLs ($N_{2,3}$). They should be heavier and explain the large masses which come from the Seesaw mechanism (see section 2.1.1) and the Baryonic Asymmetry of the Universe (BAU). In this case the fact that $N_1$ is a DM candidate leads to the assumption that its coupling is zero and we are left with two HNLs. This is also the unique aspect of $\nu M S M$. The SHiP collaboration experiment is a new facility which will allow the observation of heavy HNLs via their decay products which are SM particles. Below you can see the Feynman diagrams related to the observation processes.
Chapter 2. Neutrino Masses

Figure 2.5: Decays of heavy HNLs to SM particles (Left). Decay of D-mesons to HNLs (Right). [2]
Chapter 3

SHiP experiment

3.1 Physics motivation

In this section we will give an overview of the SHiP (Search for Hidden Particles) experiment. We will describe each part of it technically and also we will explain the physics involved.

The motivation to start building such an experiment lies on the fact that even though the Standard Model managed to explain many already predicted theories, such as the electroweak interactions including its symmetry breaking and the strong interactions, still there are some topics that remain blurred. In particular, SM explains the physics at the electroweak scale (Fermi Scale) with energy of 246 GeV. This is the typical value of energy describing processes of the electroweak theory. It is nothing else but the expectation value of the Higgs field in vacuum and is given by \( v = (G_F \sqrt{2})^\frac{1}{2} \) [19], where \( G_F \) is the Fermi coupling constant for the electroweak interactions. However, considering the mass of the Higgs boson, we can deduce that it is possible to extend our theory to the Planck scale due to the fact that its value witnesses that the current lifetime of the Standard Model vacuum is bigger than the age of the Universe itself. Also we have previously mentioned that there are other aspects of physics that we are not capable to explain only by relying on the Standard Model. For example, the non-zero mass of the neutrinos and their oscillations which automatically leads to the existence of right-handed neutrinos, the concept of Dark Matter and the Baryon Asymmetry of the Universe.

As we have said, the Higgs mechanism cannot give a concrete answer of how neutrinos obtain mass. One possible and elegant mechanism is the Seesaw mechanism.

However, there are some boundaries for the HNL masses. Let us assume that we are in the eV-scale of the Seesaw mechanism. We will refer to two cases. The first one is related to HNL masses much smaller than the active neutrinos (\( M_I << m_{\alpha I} \)). In this case we have two mass states with similar mass. It means that for each of these mass states there is equal mixing of active and sterile neutrinos. The second case refers to the inverse condition of the first one (\( M_I >> m_{\alpha I} \)). Here we can set a lower limit for the mass since we know that \( |U_{\alpha I}|^2 \approx \frac{|f_{\alpha I}|^2}{M_I^2} \). It should be noted though, there are some regions
that are excluded because of the neutrino oscillations’ results. The GeV-scale is the one that interests us.

3.1.1 Technical description of SHiP facility

The ultimate goal of this experiment is to observe particles that interact very weakly and the only way to observe them is through their decay to Standard Model particles. According to the requirements of the experiment, a beam of 400 GeV protons is necessary. One of the basic requirements is that we need a big production of hadrons since the particles we are looking for, may be products of heavy hadron decays. Another condition is to decrease the production of light hadrons, electrons, photons and muons because they might cause problems such as a fake signal in the detector. We will present a statistical analysis in the next chapter of how to reduce these backgrounds and specifically the muon combinatorial background. The facility is going to be placed at the North Area of the SPS ring at CERN. In 3.1, 3.2 figures, a geographical location is shown as well as a layout of the SHiP experiment.

![Figure 3.1: Location of the SHiP experiment at CERN.][16]

![Figure 3.2: Scheme of the SHiP experiment.][16]
3.1.2 Target

As mentioned above, we need to increase the production of heavy mesons and decrease the neutrino and muon flux. In order to achieve this we have to choose the material of the target with the smallest nuclear interaction length. In general, the nuclear interaction path is the average path to minimize the production of charged particles by a factor of $1/e$.

3.1.3 Muon Shield

Active Shield

One of the most important parts of the experiment is the muon shield. The construction of the muon shield is based on two options, the active and the passive. Below we will refer to both of them. While protons hit the target, we have a huge production of muons. Since we want to reduce their flux as we have already said, the tool is the muon shield. There are two shields, the active and the passive. The active shield consists of a $B_y = 40$ T magnetic field in order to bend down muons of 350 GeV. A very long sequence of magnets is needed to generate the field. More specifically, 1.8 T magnets with a total length of 23 m are splitted in equal parts of 5.66 m. One basic problem of this setup is that when muons pass the first part of the magnets, their trajectory bends down and then, at the second part it bends down once again, towards the detector. This is due to the return fields. One possible solution to avoid this problem is to place the first magnet in a specific length of the z-direction ($0 < z < 19m$) in order to discriminate the muons according to their charge. Then the second magnet is placed right in front of the first one ($19 < z < 48m$) and it is also responsible for creating the return fields. There are not any muons in this region due to the discrimination that took place due to the first field. In figure 3.3 below, we can see the trajectory of muons.
Figure 3.3: The field is described by the sky blue and the return field, by the green colour. The muon with angle $-10$ mrad managed to pass into the detector and the other were deflected by the field.[16]

**Passive Shield**

The passive shield consists of a huge conical bulk of 40 m and it is made of tungsten (110 tonnes). We use tungsten because it is a material that causes very high energy loss. Still it is not enough to stop such highly energetic muons (350 GeV) and as a solution, it is added 2500 tonnes of lead and the tungsten bulk is now surrounded and extended by the additional material and gives a total length of 70 m. Even with this additional obstacle to their trajectory large amount of muons leave the passive shield and they might be scattered by the concrete walls of the main experimental hall and as a result they redirect towards the spectrometer. Also additional material (17,000 tonnes of iron) has been added between the concrete walls and the shield but still there are enough muons that tend to enter the spectrometer. A simple scheme is presented in figure 3.5 and 3.6 showing the passive shield before and after the iron additional enhancement.
Next we will give an overview of the basic part of the experiment which is the SHiP detector. After the muon shield, the tau neutrino detector follows. It consists of the neutrino target surrounded by the Goliath magnet. Then comes the Muon Magnetic Spectrometer followed by the vacuum vessel. Right after the muon magnetic spectrometer, there is Upstream Veto Tagger (UVT). In the entrance window of the decay vessel there is also the Straw Veto Tagger (SVT). The decay vessel is surrounded by the Surround Background Tagger (SBT) and at the end of it there is the Spectrometer Straw Tracker, the Spectrometer Timing Window, the Muon Detector, Electromagnetic Calorimeter and the Hadronic calorimeter. Figure 3.7 shows a scheme of the SHiP detector.
3.1.4 Neutrino Detector

The neutrino detector is made of two basic parts. The Compact Emulsion Spectrometer (CES) and the brick. Both parts are based on the Nuclear Emulsion Cloud Chamber method. This is a usual technique used to identify particles according to their different charge. When a charged particle interacts with the passive material, we observe an ionization of the material as the charged particle penetrates it and leaves a trail which has different characteristics for different particles. Also by applying a magnetic field, we are able to distinguish the different charge. In our case it is useful because it contributes to the identification of $\nu_\tau$ and $\bar{\nu}_\tau$ by detecting the different charge of the $\tau$ lepton decay products. The main tool to identify the particles is the Nuclear Emulsion Plates. They are photographic plates with a thick emulsion layer which is compact with high density. It records the trajectory of the charged particles while penetrating in it.
The brick is a unit made of 57 emulsion films and it placed just next to the compact emulsion spectrometer. It uses lead as material. The high resolution of the emulsion films gives us the possibility to fully reconstruct the event in the three dimensional space. The CES consists of three emulsion films and there are two blanks between each other which are filled with two $15 - \text{mm}$ Rohacell cells. Those cells have very low density and they are durable to a temperature peak of 220 celcius. A picture of a unitary cell of the neutrino detector is shown in figure 3.8.

**Figure 3.8:** A cell of the neutrino detector with CES and brick.[16]
The lepton \( \tau \) decay is separated in short and long decay. Short decay is described by the fact that occurs in the same lead plate of the brick. The identification occurs with respect to the vertex at the interaction point. The possible decays of \( \tau \) are shown in the table 3.1 below.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \to e^- \nu_e \bar{\nu}_e )</td>
<td>17.8</td>
</tr>
<tr>
<td>( \tau \to \mu^- \nu_\mu \bar{\nu}_\mu )</td>
<td>17.7</td>
</tr>
<tr>
<td>( \tau \to h^- \nu_e (n\pi^0) )</td>
<td>49.5</td>
</tr>
<tr>
<td>( \tau \to h^- h^- h^- \nu_e (n\pi^0) )</td>
<td>15.0</td>
</tr>
</tbody>
</table>

As we have said, in order to be able to do the discrimination with respect to the charge we need also to add a magnetic field. In this case, the Goliath magnet is the suitable tool for this operation. Its dimensions are \( 4.5 \times 3.6 \times 2.79 \, m^3 \) and two of its four sides are open for possible change of the bricks during the run if the experiment. It consists of two coils, one at the top and a second at the bottom. The distance between them is 1.05 m and can be extended to 1.5 m. It has been adjusted in a way that the field should be constant with a value of 1.5 T.

![Figure 3.9: Between the region of blue lines the magnetic field is 1.5 T and between the red ones in 1 T.][16]
Muon Magnetic Spectrometer

After the neutrino detector comes the muon magnetic spectrometer which is dedicated to detect the muons coming from the $\tau$ lepton decays and measure their momentum. The height is 10 m and the width, 4 m. It is adjusted to measure muons in the region up to $\pi/4$ angles in order to avoid measuring muons that are coming from anywhere else. Moreover, the measurement takes place with respect to the involved $\nu_\tau$ in each interaction. The walls of the spectrometer are made of twelve layers of iron with 2 cm of air between them. The thickness is 1.2 m. At its top and bottom there are two coils of twenty turns each creating a current of 1600 A and finally, a value of magnetic field around 1.57 T is produced.

**Figure 3.10:** Overview of the Muon Magnetic Spectrometer magnet.[16]
3.1.5 Vacuum Vessel

One of the most interesting tasks of SHiP experiment is the construction of the decay vessel. We have already mentioned that we must reduce the background as much as possible. In other words, we have to avoid any occurring interactions between neutrinos and muons and the air in the vessel. To prevent this, the evacuation is on the order of $10^{-6}$ bars and there is the Surround Background Tagger as an additional factor of safety.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{vacuum_vessel.png}
\caption{Vacuum Vessel of the SHiP experiment.\cite{16}}
\end{figure}
The shape of the vessel is elliptical with a 50 m decay volume which is followed by a 12 meter magnetic spectrometer. The vertical axis of the ellipse is 10 m and the horizontal is 5 m. This choice has been done in order to minimize the muon flux passing the muon shield. We have explained further up the trajectories of muons while entering the muon shield and the way they are deflected. So, recalling figures 3.3 and 3.4 and considering the choice of the shape to be elliptical, it is quite obvious that the flux is being minimized from a geometrical point of view.

The next requirement of the construction of the vessel is to find a way to stabilize the inner pressure with the outer one since it is 1 bar compared to the inner which is $10^{-6}$ bars. For this reason, the walls have been built with additional ribs on the longitudinal and transverse direction in order to keep it stable. At this point we have to mention that the structure of the walls is based on two wall layers and the space in between is filled with liquid scintillator. Thus, the ribs separate the space into cells. The determination of the thickness of the walls has been determined according to an empirical relation which is given by:

$$s = 0.47 \times \frac{D}{100} \times \left( \frac{p}{10^{-6} \times E} \times \frac{L}{D} \right)^{0.4} + c$$

[16]

$D$ describes the internal diameter, $s$ is the thickness of the walls, $E$ is the elastic modulus which is nothing else but a mechanical property of linear and elastic materials, $p$ is the pressure outside the vessel and $c$ is the corrosion index. The two windows of the elliptical vessel (start and end) are closed with a membrane made of aluminium which seals the liquid scintillator.

### 3.1.6 Surround Background Tagger (SBT)

The SBT cannot be considered as veto tagger since its function is to detect background that comes from outside the vacuum vessel. For this reason, it is based on liquid scintillator technology which offers a high efficiency.

In general, liquid scintillators consist of a mix including a solvent and fluors. When particles are passing through this mixture, scintillation takes place by exciting molecules and we can observe light.

In our case, the SBT is useful because it absorbs the energy of the incoming particle and then it re-emits it in the form of photons. This method provides a satisfying rejection of the background. The suitable condition for us regarding the highest efficiency of the tagger lies on the light yield which is crucial for the response of our detector. Also we require the absorption and the scattering lengths to be large and of course an efficient compatibility with our main instrumentation.
3.1.7 Upstream Veto Tagger

The UVT occupies an area of $4 \times 12 m^2$ right in front of the neutrino detector and almost at the beginning of the vacuum tank. It mainly reduces the background caused by neutral kaons which are produced from neutrino and muon interactions. Furthermore, muons that managed to pass the muon shield (see 3.3) and enter the vacuum vessel are detected by the UVT. Its structure is based on plastic scintillator bars giving a high efficiency and time resolution with respect to the detector. But there is a dead time by the veto detector of the order 1 ns and it leaves an inefficiency of 0.01%. So the efficiency of UVT aims at 99.9%.

Figure 3.12: Front view of the upstream veto tagger (UVT).[16]
3.1.8 Spectrometer Tracker

The spectrometer tracker plays a very important role since its goal is to fully reconstruct the tracks of the charged particles coming from hidden particles from the decay volume. The precision should be as good as at the timing detectors which we will refer to later in the chapter. The reason is the efficient rejection of the background. Four tracking stations and one dipole magnet are the basic parts of the spectrometer. They are placed symmetrically around the magnet. The orientation of the magnetic field is such to allow the measurement of the Y coordinate of the track. The X coordinate is measured according to stereo view techniques. This method relies on the three-dimensional representation of an image and since we work with simulations we need to enhance the "depth" in order to make an efficient reconstruction of the vertex in the fiducial volume. The tracking stations consist of straw tube trackers made of PET (polyethylene terephthalate) and they are 5 meters long. Studies of simulation have shown that we expect $10^7$/station in 1 second. More simply, when a particle deposits energy in 8 straws per station, with 90% efficiency on average, we obtain 5 hits with 99.5% per straw.

There is also one more veto tagger which is the Straw Veto Tagger (SVT) and reconstructs tracks from the spectrometer tracker but they come only from the upstream veto tagger (UVT).

One crucial problem that we might have to deal with, is that the 5-meter long straws are exposed simultaneously in gravitational, electric as well as mechanical forces. This makes the tubes to be flexible and considering the fact that they are placed horizontally, a deflection might occur. This will contribute as a correction factor.
3.1.9 Spectrometer Timing Detector

As we will see in the next chapter more precisely, in order to avoid fake signal by random combinations of muons, we need a timing window which provides the possibility of time coincidence between two tracks. Since our detector has a timing resolution of 1 ns, we need higher resolution which is provided by the timing detector.

There are two options regarding the building of the timing detector. For the first one, it has been suggested to use scintillator bars made of plastic where the length varies from 1 to 6 meters. For the extraction of the signal information photomultipliers (PMTs) are going to be used. The structure of the timing detector consists of two columns with the scintillator bars placed horizontally in between. There is an overlapping region between the bars in order to avoid any loose of signal.

The second option is the Multi Gap Resistive Plates (MRPCs). Its manufacture is based on glass layers separated by simple nylon lines in between for making gaps for the gas. Resistive paint has been added to the external glass plates in order to create electrodes. The inner ones remain untouched. Consequently, when the particles travel through it and cause ionization within the gas we can read the required information.
3.1.10 Electromagnetic Calorimeter

Charged particles such as electrons, pions and photons \((e^\pm, \pi^{\pm0}, \gamma)\) are detected by the electromagnetic calorimeter. Its goal is to discriminate signal and background events using timing resolution at the scale of a few ns as well as reconstruction of \(\pi^0\) for range \(0.6 - 100\text{GeV}\). It is located \(37.2m\) in front of the middle of the decay vessel.

The electromagnetic calorimeter is made of pieces side by side of scintillator and lead. In order to obtain a resolution of the order of \(\frac{\sigma(E)}{E} \approx \frac{6\%}{\sqrt{E}}[1]\), we need \(1mm\) thick lead sheets and \(2mm\) of plastic scintillator plates. The light information by the electromagnetic showers is gathered by WLS fibers. They are doped with specific dyes which absorb the blue light coming from the scintillator and then it is re-emitted in green. After that, the light is driven through the fibers to photomultipliers in order to be enhanced.
3.1.11 Hadronic Calorimeter

The goals of the hadronic calorimeter is also to be able to offer timing resolution information for the discrimination between signal and background. Its priority is to identify pion and especially in low momenta ($< 5 GeV/c$). It is located just behind the electromagnetic calorimeter and its structure is mainly based on layers separated in active and inactive meaning that the active layers are scintillator tiles of $5 mm$ thickness and the inactive are $15 mm$ thick iron layers. The light information also is collected by photomultipliers. A basic requirement is also the distinction between pions ($\pi$) and muons ($\mu$). It depends on the geometry in the sense of how much material is going to be used in front of the muon detector which follows next. The suitable method is to reduce the material amount in front of the muon detector in order for tracks of high momentum to be identified by the muon detector.
3.1.12 Muon Detector

The muon detector aims to detect muons coming from the HNL decay $N \rightarrow \pi^+\mu^-$ and $N \rightarrow \mu^+\mu^-\nu_\mu$. It has been also designed to separate signal from background based on decays of kaons coming from interactions of the surrounded material of the decay vessel ($K_L \rightarrow \pi^\pm\mu^\mp\nu_\mu$ and $K_S \rightarrow \pi^+\pi^-$).

For the channel $N \rightarrow \pi^+\mu^-$, almost 3% of the pions are decayed into muons and neutrinos before they even enter in the first detection area so they are not good candidates. Their momentum is below 3\,GeV. On the other hand, muons with momentum between 3 and 100 GeV pass the calorimeter. In addition, for the channels $N \rightarrow \pi^+\mu^-$ and $N \rightarrow \rho^+\mu^-$, the detector should separate the combinatorial muons that come from the target and might be misidentified as pions. This can be achieved with the timing window detectors and also we know that muons that are produced in the target, their distribution is uniform in the spill compared to the decay products of $K_L, K_S$ which arrive almost at the same time at the detector.

It is located right in front of the calorimeter and its structure is based on four stations consisted of active layers with three muon filters in between. The active layers are plastic scintillator strips where WLS fibers are used to extract the information by detecting the light.
After matching the tracks in the tracking stations with the hits in the muons system, they will be identified as muons or hadrons based on their pattern recognition and their energy left at the calorimeters (hadronic or electromagnetic).

![Image of muon detector's active layers with muon filters in between.](image)

**Figure 3.18**: Muon detector’s active layers with muon filters in between.\[16\]

In the next chapter we will refer to the physics involved for this setup.
Chapter 4

Background sources and HNL signal

One of the most important aspects of the experiment is to reduce the background below one event in a five-year run which corresponds to $2 \times 10^{20}$ protons on target as we have already mentioned.

The basic sources of the dangerous background are muons and neutrinos. In particular, muons and neutrinos which are products of hadron decays related to the interactions of the protons with the target, may interact with the material of the walls in the vacuum vessel and can fake our signal. Also, combinations of tracks which manage to pass the muon shield cause a fake event. A third factor that can cause problems to our signal is the cosmic background.

4.1 Background caused by neutrinos

As protons hit the target, pions ($\pi^{\pm}$) and kaons are produced. Neutrinos coming from their decay may survive the hadron absorber and the muon shield. Those are mainly $\nu_\mu$. [1]

The neutrinos mainly interact with the material of the muon magnetic spectrometer in the tau neutrino detector, with the walls in the decay vessel and with the material in the entrance of the decay vessel. Almost 80% is due to the interactions in the vessel tank. They interact via deep inelastic scattering (DIS) and produce $V^0$ particles. The name is a characteristic of the decay since they produce a "V" shape while they decay. This kind of decay might take place in the decay volume and the probability for a fake signal is being increased. A representative sample obtained by simulations, shows that we expect $10^7$ neutrino interactions corresponding to $2 \times 10^{20}$ protons on target. Almost $10^4$ events have been reconstructed in the hidden sector spectrometer and they are considered as signal candidates. The upstream veto tagger (UVT) rejects the background coming from neutrino interactions with the material of the muon spectrometer of the tau neutrino detector. Background caused by interactions with the material of the entrance to the decay vessel, is being rejected by the straw veto tagger (SVT). An additional rejection factor is caused by the liquid scintillator (see 3.1.5) in the area of the decay volume.
Also, we have to apply some selection cuts in order to additionally reduce the background. So, the fact that we need two tracks with $\chi^2/\text{ndof} < 2.5$, $\text{ndof} > 10$, $\text{doca} < 30\text{cm}$ and $\text{IP} < 2.5\text{m}$ rejects the background 99.4% of the total neutrino background reconstruction. $\text{ndof}$ is the number of degrees of freedom, $\text{doca}$ is the distance of closest approach between two tracks and $\text{IP}$ is the impact parameter to target. In the table 4.1 below you can see the rejection factors for different parts of the detectors.

**Table 4.1**: The first column shows from part of the detector where the interaction took place. The second column shows the interaction that have a reconstructed vertex in the hidden sector. The third gives the number of those which have not vetoed and the last one shows the number of interaction after applying the selection cuts.[16]

<table>
<thead>
<tr>
<th>Detector</th>
<th>Reconstructed</th>
<th>Not vetoed</th>
<th>Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ detector</td>
<td>940</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>Vessel lids</td>
<td>42</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Vessel walls</td>
<td>8859</td>
<td>37</td>
<td>1</td>
</tr>
<tr>
<td>Tracking system</td>
<td>202</td>
<td>14.7</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>10044</td>
<td>52</td>
<td>56</td>
</tr>
</tbody>
</table>
4.2 Muon Inelastic Scattering background

Recalling 3.1.3, we can see that all muons reach the cavern wall while they are deflected by the muon shield and they hit it. As a result they perform inelastic scattering with the nucleus of the concrete and mostly kaons and lambda hyperons are produced ($V^0$ particles). This does not cause any serious background in our spectrometer.

Another source of background is when muons are not deflected completely and they manage to interact inelastically with the material close to the entrance of the decay vessel. This is pretty much similar to the neutrino background. According to the statistical analysis based on simulations, we conclude that for $2 \times 10^{20}$ protons on target we expect only 2 events with a 90% confidence level. [1]

4.3 Cosmic Muon Background

Another source of background is the cosmic muon background. Simulations of $9 \times 10^7$ of cosmic muons over an area of $30 \times 90 m^2$ above the setup of SHiP experiment were done in order to evaluate the caused background. These muons will be a dangerous background if they hit 3 tracking stations and they also have a $\chi^2/ndof < 25$ for each track. The distance of closest approach between them is $<10cm$ and their reconstructed vertex is in the fiducial volume. The fiducial volume of the experiment is set to be between the first veto tagger which is placed 5 m from the entrance of the vacuum vessel and the first straw tracker at the SHiP detector. Finally, their impact parameter with respect to the target results to be $>33m$ and as a consequence all of them have been excluded.

One other basic problem, cosmic muons might cause, is the generated background which is due to the deep inelastic scattering (DIS) with the nucleus of the mainly the exposed parts of the experiment such as the concrete walls and the liquid scintillator of the vacuum tank. Data based on simulations showed that this type of background is not dangerous at all since all the reconstructed tracks after applying cuts are rejected completely.

Next we will refer to the HNL signal.

4.4 HNL signal

There is a strong dependence between the hierarchy of the active neutrino masses and the HNL couplings to the three flavours of Standard Model $U^2_{e,\mu,\tau}$. According to the theory there are five scenarios which are shown below.

- $U^2_{e} : U^2_{\mu} : U^2_{\tau} \approx 52 : 1 : 1$ (Inverted hierarchy)
- $U^2_{e} : U^2_{\mu} : U^2_{\tau} \approx 1 : 16 : 3.8$ (Normal hierarchy)
- $U^2_{e} : U^2_{\mu} : U^2_{\tau} \approx 0.061 : 1 : 4.3$ (Normal hierarchy)
Chapter 4. Background sources and HNL signal

- $U^2_e : U^2_\mu : U^2_\tau \approx 48 : 1 : 1$ (Inverted hierarchy)
- $U^2_e : U^2_\mu : U^2_\tau \approx 1 : 11 : 11$ (Normal hierarchy) [16]

Our simulation is based on the second scenario considering the mass of HNL to be $1\text{GeV}/c^2$ and $0.6\text{GeV}/c^2$. The simulation is based on the second scenario considering the mass of HNL to be $1\text{GeV}/c^2$. There are some criteria to accept a simulated HNL in order to be able to pass it to the reconstruction. First of all, its vertex should be in the fiducial volume. Its daughters should leave their signature in the two straw stations before the magnet and also after. For the case of $HNL \rightarrow \mu \pi$ and $HNL \rightarrow e e \nu$, they should deposit energy at the electromagnetic calorimeter and finally for the decay $HNL \rightarrow \mu \mu \nu$, the two muons should be detected by the two muon stations.

A simulation of one million HNLs has been prepared for masses $1\text{GeV}/c^2$ and $0.6\text{GeV}/c^2$. Below you can see the kinematic parameters for both HNL masses mentioned above.

![Figure 4.1: Reconstructed mass, impact parameter to target, maximum $\chi^2/ndf$ and distance of closest approach for HNL mass $1\text{GeV}/c^2$.](image)
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Figure 4.2: Z-position of the reconstructed vertex for HNL mass $1\text{GeV}/c^2$.

Figure 4.3: Minimum number of degrees of freedom for HNL mass $1\text{GeV}/c^2$.

Figure 4.4: Reconstructed mass, impact parameter to target, maximum $\chi^2/\text{ndf}$ and distance of closest approach for HNL mass $0.6\text{GeV}/c^2$. 
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Figure 4.5: Zoomed in version of distance of closest approach for HNL mass $1\text{GeV}/c^2$.

Figure 4.6: Z-position of the reconstructed vertex for HNL mass $0.6\text{GeV}/c^2$.

Figure 4.7: Minimum number of degrees of freedom for HNL mass $0.6\text{GeV}/c^2$. 
Chapter 5

Muon Combinatorial Background

While protons hit the target huge amount of muons are produced from different protons on target. Many of them survive by passing the muon shield or deflect from the cavern walls and enter the vacuum vessel. In this case random combinations of such muons may fake our real signal since our muon tracks, that are products of a HNL decay, have a similar final state. The first requirement in order to suppress the muon combinatorial background is a time window of $340\, ps$\textsuperscript{[13]}. It means that the tracks which enter the SHiP detector should have a time difference of $340\, ps$ between each other. This requirement reduces the background by a factor of $10^{-7}$\textsuperscript{[13]}. The time difference is based on the timing window detector (see 3.1.9) Moreover, the upstream veto taggers and the surrounding veto tagger contribute to the suppression by an additional factor of $10^{-4}$\textsuperscript{[13]}. Below we will present a statistical analysis in order to make an evaluation of the rate of the dangerous background and see how many of them managed to survive in the SHiP detector and could give us the fake signal. In SHiP experiment we expect the production of $2 \times 10^{20}$ protons on target. It is impossible to simulate such an amount of muons with our current instrumentation in a very limited time. In order to overpass this obstacle, we prepared a fast simulation with only muon combinatorial background events. This sample has been generated by simulating single muons. Then two tracks were combined by two

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track $P$</td>
<td>$&gt; 1.5, GeV/c$</td>
</tr>
<tr>
<td>Track $\chi^2/ndof$</td>
<td>$&lt; 25$</td>
</tr>
<tr>
<td>di-muon DOCA</td>
<td>$&lt; 1, cm$</td>
</tr>
<tr>
<td>di-muon vertex</td>
<td>$fiducial$</td>
</tr>
<tr>
<td>di-muon mass</td>
<td>$0.2, GeV/c^2$</td>
</tr>
<tr>
<td>IP w.r.t. target</td>
<td>$&lt; 2.5, m$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$8 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
different simulated events. Based on that statement, an additional re-
jection with a factor of $10^4$ is given due to the fact that those muons,
since they are not coming from a unique HNL decay, and their kinem-
atic is off the fiducial volume. Required cuts also which are in the

table 5.1.

At the first step of our analysis, we have generated a sample of 1
million muons (half $\mu^+$ and half $\mu^-$) with the already mentioned re-
quirements and we passed them through simulation and reconstruc-
tion in order to check how many of them have survived the muon
shield. In the simulation, we have used the active muon shield. Fair-
Ship, a software dedicated to SHiP experiment has the option to per-
form fast simulations for generation of background. The distribu-
tions of momentum ($P$) versus $\eta$ (pseudorapidity) at the origin and
after the muon shield are presented below in figures 5.1 and 5.2. The
origin is their production point.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.1.png}
\caption{$P$ versus $\eta$ at the origin.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.2.png}
\caption{$P$ versus $\eta$ after the muon shield.}
\end{figure}
The trajectory of the muons is not straight all the way from the origin to the detector mainly due to the existence of muon shield and its magnetic field (see 3.1.3). As a consequence, there is a change of $\eta$ at the SHiP detector for a given region at the origin. The efficiency is nothing else but those muons who survived the muon shield compared to the initial amount of muons. So the efficiency is given by the ratio: $\text{efficiency} = \frac{N_{\text{survived}}}{N_{\text{origin}}}$. Below you see efficiency curves for several $\eta$ regions at the origin.

**Figure 5.3:** Fitted efficiency curve in logarithmic scale extrapolated to zero for $\eta(3.000 - 4.000)$ at the origin.

**Figure 5.4:** Fitted efficiency curve in logarithmic scale extrapolated to zero for $\eta(4.000 - 4.170)$ at the origin.
Chapter 5. Muon Combinatorial Background

**Figure 5.5:** Fitted efficiency curve in logarithmic scale extrapolated to zero for $\eta(4.170 - 4.333)$ at the origin.

**Figure 5.6:** Fitted efficiency curve in logarithmic scale extrapolated to zero for $\eta(4.333 - 4.500)$ at the origin.
The next step of our analysis is based on a sample of combinatorial background muons with more realistic kinematics compared to the sample from the first step where the distributions are flat. It contains almost 10 million muons ($\mu^+, \mu^-$) with only information referred to the origin. In other words, this sample has not passed through any simulation and reconstruction. Each event in these plots has a weight which corresponds to $10^{12}$ muons. This is due to the fact that it is impossible to simulate $10^{20}$ muons. So in this way we manage to obtain statistics which correspond to $5 \times 10^{13}$ protons on target. The reason we used this sample is that we need to apply the realistic conditions to the sample in the first step of the analysis when
estimating the impact parameter to target, the z-position of the vertex, the distance of closest approach and the mass of the HNL candidates from muon combinatorial background. This method aims to give us an estimate for the muon combinatorial background.

First of all, we have to transfer the information of the efficiency curves, obtained from the first step of the analysis, to the sample with the realistic kinematics in order to estimate the rate of muons entering the vacuum vessel (see figure 5.14).

As we said further up, at the same time we need to adjust the conditions of the sample with realistic kinematics to the sample which
Figure 5.11: Fitted efficiency curve in logarithmic scale extrapolated to zero for $\eta(5.667 - 8.000)$ at the origin.

has a uniform distribution. This information can be obtained by getting the ratio of the momentum and $\eta$ distributions for the two samples and apply it while rebuilding the distance of closest approach between the two muon tracks, their z position of the vertex and their impact parameter to target. Below you can see the distributions the distribution of how many we expect in one spill 5.12 as well as the distribution including the information of how many of muons have survived the muon shield and entered the vacuum vessel per spill 5.14. Figure 5.14 contains the weights from the efficiency curves as well as weights corresponding to 10000 muons per event. So we have an estimate of those who survived the muon shield.

We have to mention that referring to the term spill, we mean that the protons on target arrive in bunches and not continuously. The time difference between two spills is $\approx 1 \text{ second}$. 
Figure 5.12: Momentum ($P$) distribution at the origin with weights.

Figure 5.13: Pseudorapidity $\eta$ distribution at the origin with weights.
Chapter 5. Muon Combinatorial Background

Figure 5.14: Momentum ($P$) distribution at the origin with weights corresponding to the amount of muons that survived the muon shield.

Figure 5.15: Zoomed in version of figure 5.14 for range $0 - 50$ GeV.
5.0.1 Background estimate

We will now get an estimate of the number of events which are found at the SHiP detector considering all the extracted information so far. As we have already said, the veto tagger gives a rejection of the order of $10^{-4}$. Additional rejection of $10^{-7}$ is given by the timing window detector. From the integration of the figure 5.14 we can extract the information for the rate of muons inside the decay volume which is found to be $75 \times 10^3$ muons/second or 75 kHz (see figures 5.18, 5.17). This is the rate of those who survived the muon shield. We also know that the number of seconds in one spill is 1 s (with a top of 1.2 s[1]). So, the rate is given by the ratio of the number of events expected in one spill to survive the muon shield and the number of seconds in one spill. Finally, we have 75 kHz. So we get:

$$N_{\text{spill}} = 75 \times 10^3 \text{Hz} \times 10^{-4} \times 10^{-7} = 75 \times 10^{-8} \text{events}$$

This is the number of muons in 1 spill. Furthermore, cuts have been applied according to the table 5.1. We have extracted that an additional rejection factor of $8 \times 10^{-3}$ is added. Now considering that the experiment will run for 5 years, we have:

$$N_{\text{total}} = 75 \times 10^3 \text{Hz} \times 10^{-4} \times 10^{-7} \times 8 \times 10^{-3} \times 5 \times 10^6 = 3 \times 10^{-2} \text{events}$$

Finally we are left with 0.03 events in a 5 year run.

Below you can see the impact parameter to the target, the z position of the vertex, the distance of closest approach between two tracks and the di-muon mass of the muon combinatorial background. The impact parameter (IP) is the perpendicular distance between the path of the muon and the hypothetical straight trajectory directly
from target to the detector. The vertex describes the point where a decay takes place and the distance of closest approach is the closest distance between two muon tracks while they are found in the SHiP detector. The plots are normalized to unit area.

**Figure 5.17:** Zoomed in version of the integrated plot 5.14 for range 0 – 50 GeV/c.

**Figure 5.18:** Left: Zoomed in version of the integrated plot 5.14 for range 50 – 150 GeV/c. Right: Zoomed in version of the integrated plot 5.14 for range 150 – 250 GeV/c.
Chapter 5. Muon Combinatorial Background

**Figure 5.19:** Di-muon mass for the muon combinatorial background.

**Figure 5.20:** Impact parameter to target including information of realistic kinematics.

**Figure 5.21:** Distance of closest approach between two tracks with realistic information included.
Figure 5.22: z-position of the vertex for two muon tracks in the fiducial volume with realistic information applied.
Chapter 6

Conclusions

- The \( \nu \)SM is an extension of the SM which tries to explain the neutrino oscillations and how they obtain mass. It can be achieved by introducing three right-handed massive neutrino states, the HNLs. The lightest of the HNLs is considered to be a DM candidate. Also, Baryon Asymmetry of the Universe can be explained via the CP violation processes.

  Background Summary

  The thesis is dedicated to estimate the muon combinatorial background over a 5 year run.

- The basic factors that mostly contribute in order to reject the muon combinatorial background is the IP and the distance of closest approach. The muon combinatorial background is also being suppressed by the additional rejection occurred by the timing window detector and the veto tagger. Because of that we have an additional rejection of the order of \( 10^{-9} \) as we have already said. Finally the kinematic requirements offer a rejection of the order of \( 8 \times 10^{-3} \) as we have seen in the analysis. We have deduced that the expected number of events at SHiP over a 5 year run is 0.03 events.
Bibliography


[5] Eduardo Fradkin. “Chap.7 Quantization of the Free Dirac Field”. In: 3 ().


