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Doctoral Thesis

Search for heavy neutral leptons in events with three charged leptons in pp collision at $\sqrt{s} = 13$ TeV at CMS detector

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"That is fundamentally the only courage which is demanded of us: to be brave in the face of the strangest, most singular and most inexplicable things that can befall us. The fact that human beings have been cowardly in this sense has done endless harm to life; the experiences that are called "apparitions", the whole of the so-called "spirit world", death, all these things that are so closely related to us, have been so crowded out of life by our daily warding them off, that the senses by which we might apprehend them are stunted. To say nothing of God. But fear of the inexplicable has not only impoverished the existence of the solitary man, it has also circumscribed the relationships between human beings, as it were lifted them up from the river bed of infinite possibilities to a fallow spot on the bank, to which nothing happens."

Rainer Maria Rilke

UNIVERSITEIT GENT

Summary

Faculty Name
Department of Physics and Astronomy

Doctor of Philosophy

Search for heavy neutral leptons in events with three charged leptons in pp collision at $\sqrt{s} = 13$ TeV at CMS detector

by Martina VIT

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Chapter 3

Heavy Neutral Leptons

In the Standard Model, all the fermions are known to have both, left and right handed chirality, the only exception comes from the neutrinos.

The recent neutrino oscillation experiments have clearly and definitely shown that neutrinos are massive; thus in this scenario, including the hypothesis of the existence of the right handed neutrinos, ν_R or *Heavy Neutral Leptons* (HNLs), the light ν_{SM} flavor oscillations can be explained via the type I seesaw mechanism [1] [2] [3] [4]. Another strong possible endorsement comes from the possibility to consider the ν_R as part of the explanations for the baryon asymmetry of the universe; the mixing between ν_R violates CP and the interaction of the ν_R may potentially generate a matter-antimatter asymmetry in the early stage of the formation of the universe [5] [6].

These few examples, which are going to be explored later on, show already the relevance and the interest of the HNL program and the strong motivations behind the existence of the ν_R. This huge enthusiasm has lead in the past $\sim$ 10 years to the creation of a very active community with strong synergy between the theory people and the experimental collaborations which has brought to the publication of an impressive numbers of papers and the proposal of a consistent number of experiments focused manly on heavy neutral leptons.

3.1 Neutrino Portal

The *neutrino portal* is determined as coupling of one or more dark fermions N ($N_I = 1, 2, ...\, \mathcal{N}$), which are sterile with respect to the SM gauge interactions, to the gauge-invariant operator $(\bar{L}_\alpha \cdot \widetilde{\Phi})$; the general form of the neutrino portal could be displayed as:

$$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \sum F_{\alpha I}(\bar{L}_\alpha \cdot \widetilde{\Phi})N_I + h.c. \tag{3.1}$$

where the summation loops over the flavor of lepton doublets L_α ($\alpha = e,\ \mu,\ \tau$) and the number of available HNLs N_I; $F_{\alpha I}$ are the Yukawa couplings and Φ is the Higgs doublet. The term $\mathcal{L}_{DS}$ should contain the mass term of HNL which can be both Majorana or Dirac [7]. Fixing the Φ to its vacuum expectation value, $\widetilde{\Phi} = \frac{1}{\sqrt{2}}\binom{v}{0}$, and diagonalize the mass term of the dark fermions, the last term in Eq. 3.1 brings to the quadratic mixing of the neutrinos ν_α with the N_I; this mixing is parametrized by a matrix V. In the minimal HNL models, the elements of the matrix V control both the production and the decay of the HNLs (see fig. 3.2). If $\mathcal{N} = 3$, there is a right-chiral counterpart for each ν_{SM}, see fig. 3.1. The fermion N_I can have mass M_I which is independent of the value of $F_{\alpha I}$.

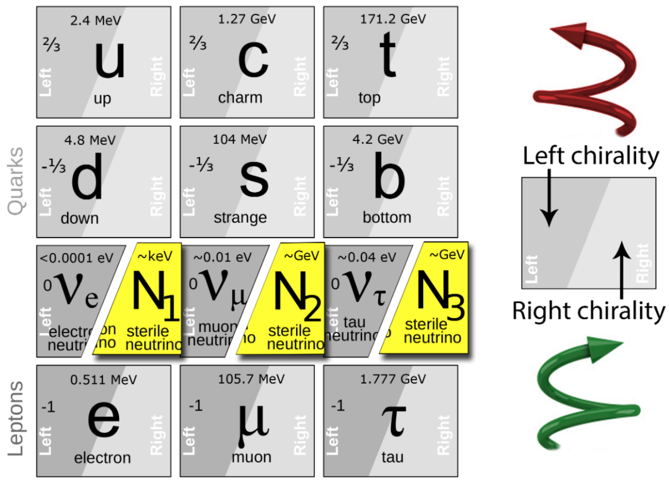

FIGURE 3.1: There are 3 SM neutrinos ν_e, ν_μ, ν_τ which are massless and always left-chiral; 3 right-chiral counterparts are added N_1, N_2, N_3. They are sterile so they do not feel the electric, weak and strong forces

Considering the existing searches and considering a model-indipendent phenomenological approach, we could assume the existence of only a *single* light HNL which is light enough to be kinematically accessible at the accelerator experiments; see full overview in [8].

There are then only two free parameters to be constrained: the mass M_I of the HNL and its coupling with the SM neutrino of flavor α controlled by the Yukawa coupling $F_{\alpha I}$. Without any signal excess, upper limits are settled on the mixing parameter $|V_{\alpha I}^2|$ $(= |F_{\alpha I}^2|)$ as function of the M_I for a given flavor α. It is frequently assumed that in the matrix V the other mixing elements for the residual flavors are zero; this latter consideration, in spite of the fact that does not translate into a valid concrete model, it is very useful to extract generic limits on the single $|V_{\alpha I}^2|$ without involving any model dependent hierarchy between the different flavor mixings.

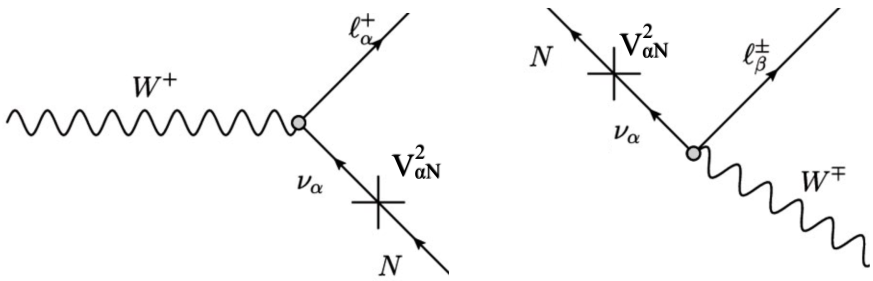

FIGURE 3.2: Production (left) and decay (right) of the particle N_I.

3.2 Heavy neutral lepton formalism and extension of the standard model

To set up our notation and convention, we first discuss the formalism for the simplest extension of the SM which includes right handed singlets. In the next section (3.3), we will try to contextualize the theory, here explained, summarizing the current constraints on the mass and mixing of a heavy neutrino from various direct detection experiments, accelerator searches and electroweak precision constraints.

3.2.1 Seesaw mechanism

The most general renormalisable Lagrangian for the neutrino masses includes both the Dirac and Majorana mass terms. The SM Lagrangian $\mathcal{L}_{SM}$ is extended adding $\mathcal{N}$ right-handed neutrinos N_I: (for notations see Eq. 3.1).

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_I \partial_\mu \gamma^\mu N_I - \left(F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c. \right) \tag{3.2}$$

As already explained in the previous section (3.1), these N_I are neutral with respect to all the gauge interactions of the SM, thus are called *sterile neutrinos* or *gauge-singlet fermions*. In the Higgs phase, the term 3.1 brings to the $\nu_\alpha - N_I$ mixing. As result the *charge eigenstates* of the $\mathcal{L}_{SM}$ (3.2) do not coincide with the *mass eigenstates*, which can be extracted diagonalizing the following matrix:

$$\mathcal{M}_{\nu,N} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_I \end{pmatrix} \tag{3.3}$$

with $m_D = 3 \times \mathcal{N}$ Dirac mass matrix, $(m_D)_{\alpha I} = F_{\alpha I} v,\ v = \sqrt{2}\langle \Phi \rangle$ and M_I is $\mathcal{N} \times \mathcal{N}$ matrix of Majorana masses.

Considering the relation between M_I and m_D, we could explore two interesting extreme limits:

Pure Majorana neutrino, $m_D \ll M_I$. In this limit, the mass matrix give rise to 3 almost pure right-handed neutrinos with heavy Majorana mass M_I and 3 almost pure left-handed neutrinos with light Majorna mass $m_\nu = -(v m_D)^T M_I^{-1} (v m_D)$ which are the 3 eigenvalues of the matrix $(\mathcal{M}_\nu)_{\alpha\beta}$. This mechanism is then referred to as the *seesaw mechanism*[1] [1] [11] [12]. There are then the other $\mathcal{N}$ eigenstates of the $\mathcal{M}_{\nu,N}$ which almost coincide with the N_I up to a small admixture of ν_α. The magnitude of this mixing is given by the ratio of the Dirac and Majorana masses → *mixing angle* or *active-sterile mixing*:

$$V_{\alpha I}^2 \equiv \frac{v^2 |F_{\alpha I}|^2}{M_I^2} \ll 1 \tag{3.4}$$

It generates the 9 measurable neutrino mass parameters from m_D and M_I, that contain 18 unknown parameters to the Lagrangian: $number\ of\ HNL\ parameters = 7 \times \mathcal{N} - 3$. $\mathcal{N}$

[1] This mechanism is usually called *Type-I seesaw*. *Type-II seesaw* has an extra SU(2) triplet scalar [9]; in *Type-III seesaw* an extra fermion in the adjoint of SU(2) is added to the model [10]

FIGURE 3.3: Silly representation of the *seesaw mechanism* [13]. Note that for a fix value of m_D, higher is value of the m_I^R lower is the one of the m_I^L and vice-versa, from this the *seesaw* name.

are the real Majorana masses M_I plus $3 \times \mathcal{N}$ complex Yukawa coupling $F_{\alpha I}$ minus 3 phases which go to the redefinitions of ν_e, ν_μ, ν_τ.

Pure Dirac neutrino, $M_I \ll m_D$. In this limit, the mass matrix give rise to 3 Dirac neutrinos $\Psi = (\nu_L, \bar{\nu_R})$ with masses $m_\nu = m_D$. To obtain the observed neutrino masses the coupling is needed to be $F_{\alpha I} \sim 10^{-12}$ which is much smaller than the SM Yukawa couplings.

3.2.2 Considerations on Majorana and Dirac neutrinos

These paragraphs below are freely inspired by the overview given by R.D. Kauber here [14].

Distinction between Majorana and Dirac terms.

The nomenclature "Majorana" is used to define different things and it is important for the following chapters to clarify the meaning.

In the Sec. 3.2.1 *Majorana* and *Dirac* are used to refer to the mass terms in the Lagrangian 3.2. The additional meaning is related to the type of neutrino. A *Majorana* particle is defined as a particle that is its own antiparticle. A Dirac particle has an antiparticle that is distinctly different from it. Neutrino are the only particle which can be both *Majorana-Dirac* while all the other fermions are strictly Dirac-type.

Lepton Number conservation.

To be more clear and explicit, we write the Dirac mass term as:

$$-m_D(\bar{\nu_L}\nu_R + \bar{\nu_R}\nu_L) \tag{3.5}$$

and the Majorana one:

$$-\frac{1}{2}m_I^L(\bar{\nu_L}\nu_L^c + \bar{\nu_L}^c\nu_L) - \frac{1}{2}m_I^R(\bar{\nu_R}\nu_R^c + \bar{\nu_R}^c\nu_R) \tag{3.6}$$

In this way is it easier to see the interactions: ν_L destroys a left-handed (LH) neutrino and creates a right-handed (RH) $\bar{\nu_R}$, $\bar{\nu_L}$ creates a LH neutrino and destroys a RH $\bar{\nu_R}$, ν_L^c creates a LH neutrino and destroys a RH antineutrino, $\bar{\nu}_L^c$ destroys a LH neutrino and creates a right-handed antineutrino.

Looking now at the Feynman diagram of the first term of Eq. 3.5 a RH particle disappears at a point and a LH particle appears. Therefore weak (chiral) charge is not conserved, but the lepton number, however, is conserved, as we started with a neutrino (not an anti-neutrino) and ended up with a neutrino $\rightarrow$ **Dirac neutrinos conserve the lepton number**.

Same considerations can be made for the Eq. 3.6, the weak charge is not conserved and neither the lepton number. We started with zero neutrinos and ended up with two neutrinos. $\rightarrow$ **Majorana neutrinos violate the lepton number**.

Considering here (Fig. 3.4) as example the leptonic decay of the W boson from the HNL decays, if the HNL is of Majorana nature, ℓ and ℓ' (or ℓ and $\nu_{\ell'}$) can either have the same chirality (Fig. 3.4 left) or opposite chirality (Fig. 3.4 right). The former decay represents a case of lepton-number violation (LNV), while the latter decay conserves the lepton number (LNC). In the case of a HNL decay mediated by a W^* boson, a LNV decay (Fig. 3.4 top left) can lead to final states with no opposite-sign, same-flavor lepton pairs (no-OSSF), such as $e^{\pm}e^{\pm}\mu^{\mp}$ or $\mu^{\pm}\mu^{\pm}e^{\mp}$. Decays mediated by a Z^* boson (Fig. 3.4 bottom) and LNC decays (Fig. 3.4 right), instead, are always accompanied by an opposite-sign, same-flavor lepton pair (OSSF).

The HNL can couple exclusively to a single lepton-neutrino family (i.e. only one of $|\mathrm{V_{Ne}}|^2$, $|\mathrm{V_{N\mu}}|^2$, or $|\mathrm{V_{N\tau}}|^2$ is nonzero) or to multiple families (i.e. at least two of $|\mathrm{V_{Ne}}|^2$, $|\mathrm{V_{N\mu}}|^2$, and $|\mathrm{V_{N\tau}}|^2$ are nonzero at the same time). In the former case, ℓ and ℓ' (or $\nu_{\ell'}$) always belong to the same lepton generation, and the lepton flavor is conserved (LFC). If N couples to multiple lepton families instead, then the lepton flavor can be violated, $\ell \neq \ell'$ (LFV). In the LFV case, decay rates to different flavors might not be the same ($|\mathrm{V_{Ne}}|^2, |\mathrm{V_{N\mu}}|^2, |\mathrm{V_{N\tau}}|^2 > 0$, but $|\mathrm{V_{Ne}}|^2 \neq |\mathrm{V_{N\mu}}|^2 \neq |\mathrm{V_{N\tau}}|^2$).

Decay width and branching ratio

The main consideration and difference between Majorana and Dirac is that in the first case N particle is defined as a particle that is its own antiparticle. This implies that both $N_I \rightarrow W^+\ell^-$, $Z\nu_\ell$, $H\nu_\ell$ and $N_I \rightarrow W^-\ell^+$, $Z\bar{\nu}_\ell$, $H\bar{\nu}_\ell$ decay modes are open. This means that the partial width of $N_I \rightarrow W^+\ell^-$ and $N_I \rightarrow W^-\ell^+$ have the same value. Thus the total width for a Majorana neutrino and a Dirac neutrino fixing the mass are related by:

$$\Gamma_{N_I}^{Tot,\, Majorana} = 2 \times \Gamma_{N_I}^{Tot,\, Dirac} \tag{3.7}$$

This brings to the relationship between the life time:

$$c\,\tau_{N_I}^{Tot,\, Majorana} = \frac{1}{2} \times c\,\tau_{N_I}^{Tot,\, Dirac} \tag{3.8}$$

3.2.3 Prompt and long-lived HNL

The lifetime of a HNL is strongly dependent on M_{N_I} and $|V_{\alpha I}|^2$, and increases rapidly at small masses and low values of the mixing parameter (see Fig. 3.5):

$$c\,\tau_{N_I} \propto \mathrm{M_{N_I}^{-5}}|\mathrm{V_{\alpha I}}|^{-2} \tag{3.9}$$

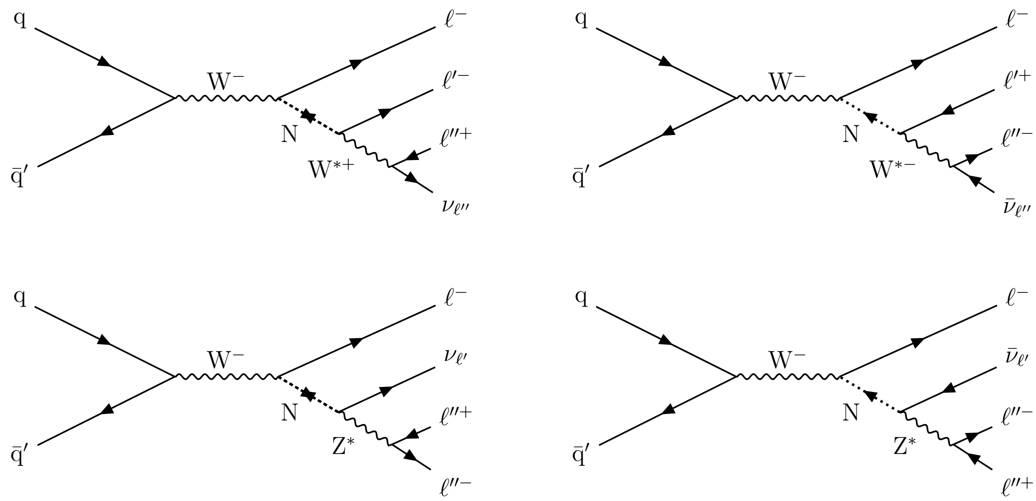

FIGURE 3.4: Typical diagrams for the production of a HNL at the LHC (N) through its mixing with a SM neutrino, leading to a final state with three charged leptons and a neutrino. The HNL decay is mediated by either a W (top row) or a Z (bottom row) boson. In the diagrams on the left, N is assumed to be a Majorana neutrino, thus ℓ and ℓ' in the W^*-mediated diagram (top) can have the same electric charge, with lepton-number violation (LNV). In the diagrams on the right instead, the N decay conserves the lepton number (LNC) and can be either a Majorana or a Dirac particle. Therefore ℓ and ℓ' in the W^*-mediated diagram (top right) have always opposite charge. If N couples exclusively to a single lepton-neutrino generation, then ℓ and ℓ' (or $\nu_{\ell'}$) always belong to the same lepton generation, and the lepton flavor is conserved (LFC). If N couples to multiple lepton families instead, then the lepton flavor can be violated, $\ell \neq \ell'$ (LFV).

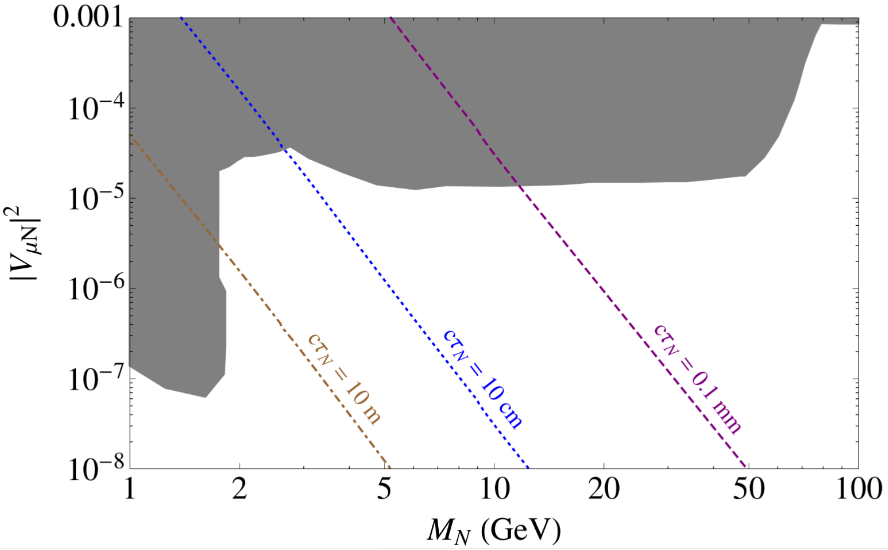

FIGURE 3.5: Lifetime $c\tau$ of a HNL as a function of its mass M_{N} and its mixing parameter $|V_{\mathrm{N}\ell}|^2$ to a single lepton family: the three oblique lines correspond to $c\tau$ values of (from left to right) 10 m, 10 cm, and 0.1 mm. The shaded grey area represents—approximately—the region of the parameter space excluded by previous searches.

As a consequence, the kinematics and acceptance of HNLs with masses below about 20 GeV are significantly affected by their long lifetimes, and must be accounted for in the signal simulation and in the result interpretation. If N has a long lifetime, in particular, its decay products ($\ell^{\pm\prime}$, $\ell^{\mp\prime\prime}$, $\nu_{\ell''}$ or $\nu_{\ell'}$, $\ell^{\pm\prime\prime}$, $\ell^{\mp\prime\prime}$, see Fig. 3.4) emerge from a secondary vertex, spatially displaced with respect to the primary vertex of the process, and distinguishable from it.

3.3 Theoretical and experimental constraints

For a complete overview of the theoretical and experimental constraints of sterile neutrinos searches see Ref [9], [15], [16], [17], [18] and [19].

Sterile neutrinos mix with the ν_{SM}, thus at small mixing the active-neutrino mass states contain a small part of sterile neutrinos. Consequently, the mass eigenstates in the HNL couple to SM particles thanks to the tiny but nonzero mixing $V_{\alpha I}$, Eq. 3.4.

In principle, in any weak processes where the ν_{SM} participates, also the HNLs do. The strength is suppressed due to the smallness of the $\nu_\alpha - N_I$ mixing angle but the kinematics properties could show the interaction due to the fact that the HNL is much more massive than the active-neutrino. Therefore, it is possible to select a particular channel and phase space which enhances some kinematics features associated to the presence of the sterile neutrino.

These properties are explored and exploited in the direct searches for HNLs.

3.3.1 Direct HNL searches

Considering the wide theoretical accessible mass ranges (MeV-TeV) and taking into account the several production and decay modes, we have a quite rich experimental landscape.

- For M_N values below 1 MeV, HNL can be probed by neutrino-oscillation experiments [20];
- for 10 eV $< M_N <$ 1 MeV, searches for $0\nu\beta\beta$ and precision measurement of $\beta-$decay energy spectra have constrained the mixing $|\mathrm{V_{Ne}}|^2$ [21];
- for 1 MeV $< M_N <$ 1 GeV, both $|\mathrm{V_{Ne}}|^2$ and $|\mathrm{V_{N\mu}}|^2$ have been constrained by *peak searches* using leptonic decay of pions and kaons like $K \rightarrow \mu(e)N$, $\pi \rightarrow \mu(e)N$ [22];
- for HNL in the MeV-GeV mass ranges, many searches through sterile neutrino decay products have been performed at beam dump experiments [23];
- for HNL in the GeV-TeV mass ranges, we enter in the domain of the leptonic and hadron colliders.

Quite often the HNL bounds are shown in the 2D plane $V_{\alpha N} \longleftrightarrow M_N$ with the assumption to fix at zero the other mixing angles which are not represented in the plot.

To have a clear overview of the current experimental (and theoretical) limits we can refer to Figs. 3.6, 3.7 and 3.8. Filled colored areas show the existing limits which, for low masses (below the charm mass), are driven by the results from beam dump experiments (PS191 and CHARM); for masses above the charm mass, the most stringent limits are the ones coming from LEP (DELPHI) and from Belle and most recently from CMS and ATLAS.

A brief experiment-focused overview follows:

- **PS191** (CERN, PS Beam 1983) [26]: the PS191 experiment was specifically design to look for neutrino decays in low energy neutrino beam. It was a detector composed of a 12 m long decay volume followed by a fine-grain calorimeter. No sterile neutrino candidates were observed but the analysis of neutrino interactions in the calorimeter shows a possible excess of events with electrons [27].
- **CHARM** (CERN, SPS beam 1985) [23]: A search for decays of HNL was performed by the CHARM Collaboration using a neutrino beam produced by dumping 400 GeV protons on a thick Copper target and looking for possible visible decays. It has been assumed the sterile neutrino to be produced by coupling in charmed D meson decays. The following decays were considered, N $\rightarrow e^+e^-\nu_e$, $\rightarrow \mu^+e^-\nu_\mu$ and $\rightarrow \mu^+\mu^-\nu_\mu$ and the limits were settle on $|\mathrm{V_{Ne}}|^2$ and $|\mathrm{V_{N\mu}}|^2 < 10^{-7}$ for N masses around 1.5 GeV. Neutrinos were assumed to be produced by neutral-current neutrino interactions in the CHARM calorimeter.
- **Belle** (KEK, asymmetric-energy e^+e^- collider, 2012) [22]: Belle collaboration performed a search on heavy neutral leptons in B-meson decays. The data sample contained 772×10^6 of $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance. The limits on the mixing parameter were obtained analyzing the $B\overline{B}$ pairs events using the leptonic and semileptonic B meson decay, $B \rightarrow X\ell\nu_R$, where $\ell = e$, μ and the X was either a charmed D meson, a light meson (π, ρ, η) or nothing (leptonic decay). Upper limits were set on on $|\mathrm{V_{Ne}}|^2$ and $|\mathrm{V_{N\mu}}|^2$ in the mass range between 0.5-5.0 GeV.

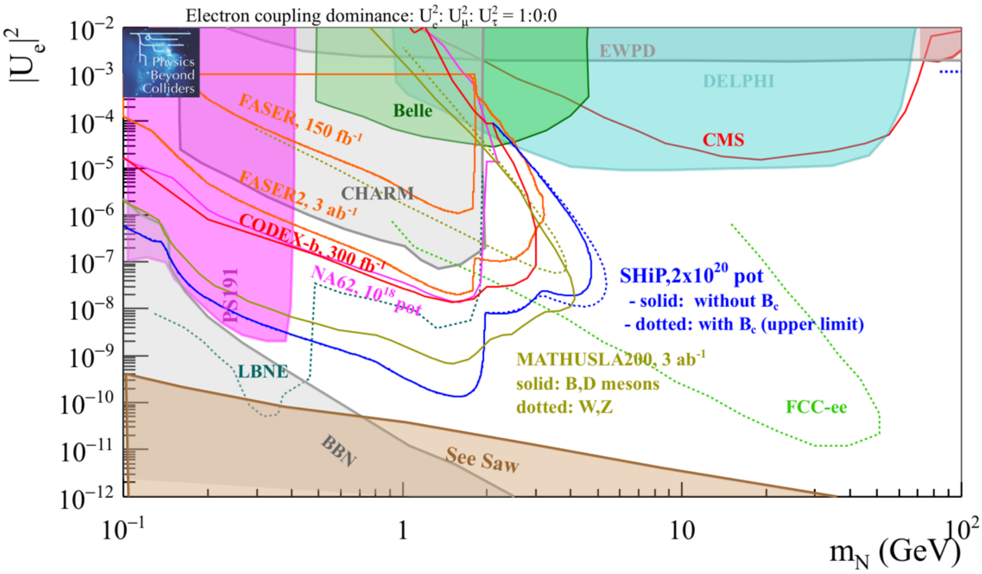

FIGURE 3.6: Sensitivity to HNL with coupling to ν_e only. Current bounds (filled areas) and 10-15 years prospects for projects (SHiP, MATHUSLA200, CODEX-b and FASER2) (solid lines). Projections for a LBNE near detector with 5×10^{21} pot and from FCC-ee with 10^{12} Z_0 decays are also shown. The gray contour named "BBN" corresponds to and HNL lifetime > 1sec, which is disfavored by BBN [24]. The brown line labeled "seesaw" represents the scale of mixing in general expected in the canonical *seesaw* . The very light gray at the top labeled as "EWPD" is the 90% C.L. exclusion limit from the electroweak precision data [25]. The other solid contours are explained in the paragraph.

- **DELPHI** (CERN, lepton collider LEP, 1997) [28]: the most stringent limits between 1 GeV and 10 GeV are still the ones been published by the DELPHI Collaboration. HNL search have been performed using the data collected by DELPHI detector corresponding to 3.3×10^6 hadronic Z_0 decays at LEP1. These results are, up to this day, one of the most interesting and most complete because they include the short-lived HNL scenario and as well the long-lived HNL scenario. For short-lived, it was considered the N production giving monojet or acollinear jet topologies, while for long-lived searchs, N was looked for checking detectable secondary vertices or calorimeter clusters. Upper limits were set for the branching ratio BR, $Z_0 \rightarrow$ N of about 1.3×10^-6 at 95% C.L. for N masses between 3.5 and 50 GeV.

- **CMS and ATLAS** (CERN, LHC pp beam 2019): there have been several searches for HNLs in both CMS and ATLAS. The ATLAS experiment recently reported on a search for HNLs using events with three charged leptons [29] using pp collision data corresponding to integrated luminosities of 32.9 to 36.1 fb^{-1}. The search is performed in channels with three muons or two muons plus one electron—providing sensitivity to $|\mathrm{V}_{\mathrm{N}\mu}|^2$ only—, where the displaced decay vertex of the HNL was exploited. CMS performed searches for HNLs only using prompt leptons, either in final states with two same-charge leptons and one or two jets ($W^{\pm(*)} \rightarrow \ell^{\pm}\mathrm{N} \rightarrow \ell^{\pm}\ell'^{\pm}q\bar{q}'$) [30], in a mass range of 20 GeV to 1.7 TeV. CMS searches with three charged leptons in the final

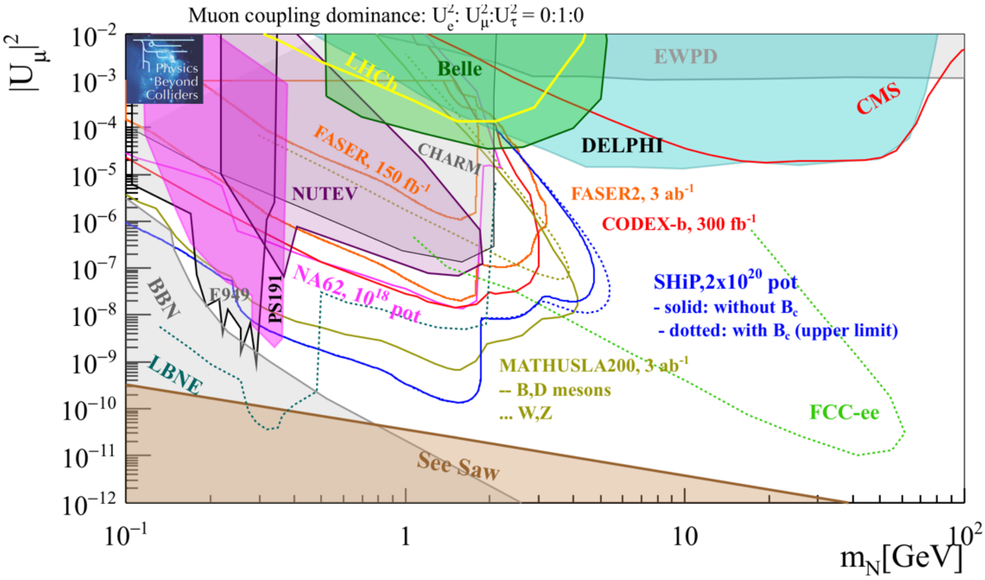

FIGURE 3.7: Sensitivity to HNL with coupling to ν_μ only. Current bounds (filled areas) and 10-15 years prospects for projects (SHiP, MATHUSLA200, CODEX-b and FASER2) (solid lines). Projections for a LBNE near detector with 5×10^{21} pot and from FCC-ee with 10^{12} Z_0 decays are also shown. The gray contour named "BBN" corresponds to and HNL lifetime > 1sec, which is disfavored by BBN [24]. The brown line labeled "seesaw" represents the scale of mixing in general expected in the canonical *seesaw* . The very light gray at the top labeled as "EWPD" is the 90% C.L. exclusion limit from the electroweak precision data [25]. The other solid contours are explained in the paragraph.

state using the leptonic W decay are going to extensively discussed in this elaborate.

3.3.2 Constraints on HNL

In the following list, we tried so summarize the current constraints coming from the theoretical predictions and from the most recent results (Figs. 3.6, 3.7 and 3.8.)

- **Searches for Charged Lepton Flavor Violation**. If we consider an HNL with a mass close to EW scale and with large off-diagonal Yukawa couplings, then this type N can lead to LFV in decays of charge leptons. Thus, testing LFV in multi-lepton searches could be an indirect way to probe the existence of HNL. Searches for such processes have placed 90% C.L. upper limits on decay branching rates, i.e. $BR(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$, $BR(\mu^+ \to e^+e^+e^-) < 1.0 \times 10^{-12}$ and $BR(\tau^- \to e^-\mu^+ mu^-) < 2.7 \times 10^{-8}$. For complete summary and references see [31].

- **Cosmological constraints on light neutrino masses**. The Planck Satellite's measurements of the large scale structures in the universe, combined with the WMAP + highL + BAO data, have set the upper limits on the sum of all the light neutrino masses [32]:

$$\sum_m m_{\nu_m} < 0.12\, eV, \quad at\ 95\%\ C.L. \tag{3.10}$$

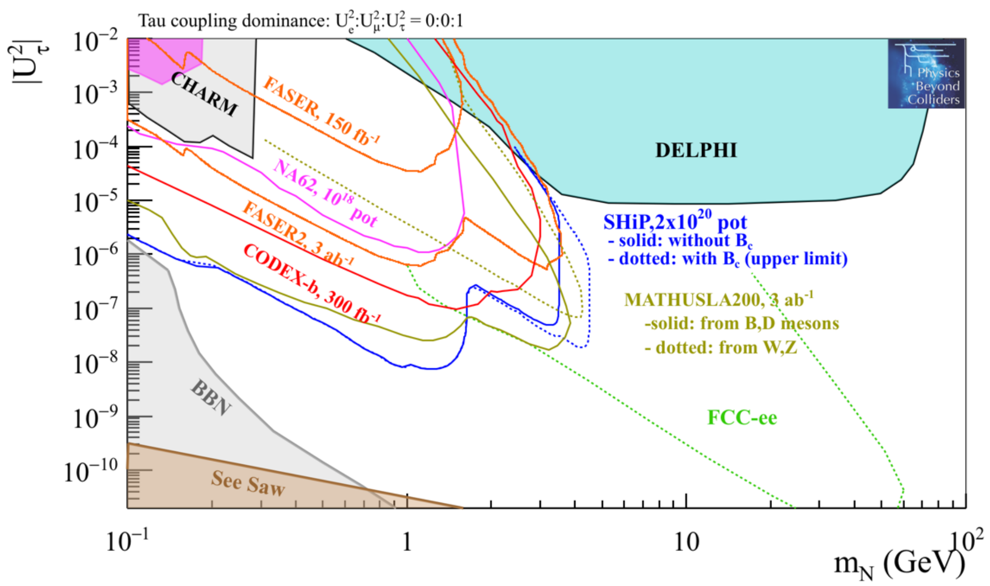

FIGURE 3.8: Sensitivity to HNL with coupling to ν_τ only. Current bounds (filled areas) and 10-15 years prospects for projects (SHiP, MATHUSLA200, CODEX-b and FASER2) (solid lines). Projections from FCC-ee with 10^{12} Z_0 decays are also shown.

- **BBN constraints**. Observing Figs. 3.6, 3.7 and 3.8, a N which falls on the left of the Big Bag Nucleosynthesis line would be able to live long enough in the early Universe to cause an overproduction of primordial Helium-4 [24].

- **Seesaw limit**. Below the line of the seesaw limit, the mixing of the sterile neutrinos with the active ones becomes too weak to be able to produce the pattern of neutrino flavor oscillations that has been observed [33].

3.4 Summary

to be re-written after: These few examples, which are going to be explored later on, show already the relevance and the interest of the HNL program and the strong motivations behind the existence of the ν_R. This huge enthusiasm has lead in the past ~ 10 years to the creation of a very active community with strong synergy between the theory people and the experimental collaborations which has brought to the publication of an impressive numbers of papers and the proposal of a consistent number of experiments focused manly on heavy neutral leptons.

Chapter 4

Search for HNL in events with three charged prompt leptons. —> 26 March

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4.4 Analysis strategy

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`\hypersetup{allcolor=blue}`.
If you want to completely hide the links, you can use:
`\hypersetup{allcolors=.}`, or even better:
`\hypersetup{hidelinks}`.
If you want to have obvious links in the PDF but not the printed text, use:
`\hypersetup{colorlinks=false}`.

Bibliography

[1] Peter Minkowski. $\mu \to e\gamma$ at a rate of one out of 109 muon decays? *Physics Letters B*, 67(4):421–428, 1977.

[2] Murray Gell-Mann, Pierre Ramond, and Richard Slansky. Complex spinors and unified theories, 2013.

[3] Rabindra N. Mohapatra and Goran Senjanović. Neutrino mass and spontaneous parity nonconservation. *Phys. Rev. Lett.*, 44:912–915, Apr 1980.

[4] J. Schechter and J. W. F. Valle. Neutrino masses in su(2) $\bigotimes$ u(1) theories. *Phys. Rev. D*, 22:2227–2235, Nov 1980.

[5] Laurent Canetti, Marco Drewes, and Mikhail Shaposhnikov. Matter and antimatter in the universe. *New Journal of Physics*, 14(9):095012, sep 2012.

[6] V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov. On anomalous electroweak baryon-number non-conservation in the early universe. *Physics Letters B*, 155(1):36–42, 1985.

[7] Sergey Alekhin, Wolfgang Altmannshofer, Takehiko Asaka, Brian Batell, Fedor Bezrukov, Kyrylo Bondarenko, Alexey Boyarsky, Ki-Young Choi, Cristóbal Corral, Nathaniel Craig, David Curtin, Sacha Davidson, André de Gouvêa, Stefano Dell'Oro, Patrick deNiverville, P S Bhupal Dev, Herbi Dreiner, Marco Drewes, Shintaro Eijima, Rouven Essig, Anthony Fradette, Björn Garbrecht, Belen Gavela, Gian F Giudice, Mark D Goodsell, Dmitry Gorbunov, Stefania Gori, Christophe Grojean, Alberto Guffanti, Thomas Hambye, Steen H Hansen, Juan Carlos Helo, Pilar Hernandez, Alejandro Ibarra, Artem Ivashko, Eder Izaguirre, Joerg Jaeckel, Yu Seon Jeong, Felix Kahlhoefer, Yonatan Kahn, Andrey Katz, Choong Sun Kim, Sergey Kovalenko, Gordan Krnjaic, Valery E Lyubovitskij, Simone Marcocci, Matthew Mccullough, David McKeen, Guenakh Mitselmakher, Sven-Olaf Moch, Rabindra N Mohapatra, David E Morrissey, Maksym Ovchynnikov, Emmanuel Paschos, Apostolos Pilaftsis, Maxim Pospelov, Mary Hall Reno, Andreas Ringwald, Adam Ritz, Leszek Roszkowski, Valery Rubakov, Oleg Ruchayskiy, Ingo Schienbein, Daniel Schmeier, Kai Schmidt-Hoberg, Pedro Schwaller, Goran Senjanovic, Osamu Seto, Mikhail Shaposhnikov, Lesya Shchutska, Jessie Shelton, Robert Shrock, Brian Shuve, Michael Spannowsky, Andy Spray, Florian Staub, Daniel Stolarski, Matt Strassler, Vladimir Tello, Francesco Tramontano, Anurag Tripathi, Sean Tulin, Francesco Vissani, Martin W Winkler, and Kathryn M Zurek. A facility to search for hidden particles at the CERN SPS: the SHiP physics case. *Reports on Progress in Physics*, 79(12):124201, oct 2016.

[8] Anupama Atre, Tao Han, Silvia Pascoli, and Bin Zhang. The search for heavy majorana neutrinos. *Journal of High Energy Physics*, 2009(05):030–030, may 2009.

[9] Frank F Deppisch, P S Bhupal Dev, and Apostolos Pilaftsis. Neutrinos and collider physics. *New Journal of Physics*, 17(7):075019, aug 2015.

[10] Robert Foot, H. Lew, X. G. He, and Girish C. Joshi. Seesaw Neutrino Masses Induced by a Triplet of Leptons. *Z. Phys. C*, 44:441, 1989.

[11] Rabindra N. Mohapatra and Goran Senjanovic. Neutrino Mass and Spontaneous Parity Nonconservation. *Phys. Rev. Lett.*, 44:912, 1980.

[12] Tsutomu Yanagida. Horizontal gauge symmetry and masses of neutrinos. *Conf. Proc. C*, 7902131:95–99, 1979.

[13] Matthew R. Francis. Neutrinos on a seesaw, 2016.

[14] Robert D. Klauber. The Seesaw Mechanism.

[15] Yi Cai, Tao Han, Tong Li, and Richard Ruiz. Lepton Number Violation: Seesaw Models and Their Collider Tests. *Frontiers in Physics*, 6:40, 2018.

[16] F. del Aguila, J. de Blas, and M. Pérez-Victoria. Effects of new leptons in electroweak precision data. *Phys. Rev. D*, 78:013010, Jul 2008.

[17] Marco Drewes, Björn Garbrecht, Dario Gueter, and Juraj Klarić. Testing the low scale seesaw and leptogenesis. *Journal of High Energy Physics*, 2017(8), Aug 2017.

[18] Marco Drewes and Björn Garbrecht. Combining experimental and cosmological constraints on heavy neutrinos. *Nuclear Physics B*, 921:250–315, 2017.

[19] Stefan Antusch and Oliver Fischer. Non-unitarity of the leptonic mixing matrix: present bounds and future sensitivities. *Journal of High Energy Physics*, 2014(10), Oct 2014.

[20] André de Gouvêa. Seesaw energy scale and the lsnd anomaly. *Physical Review D*, 72(3), Aug 2005.

[21] M. Agostini, M. Allardt, E. Andreotti, A. M. Bakalyarov, M. Balata, I. Barabanov, M. Barnabé Heider, N. Barros, L. Baudis, C. Bauer, N. Becerici-Schmidt, E. Bellotti, S. Belogurov, S. T. Belyaev, G. Benato, A. Bettini, L. Bezrukov, T. Bode, V. Brudanin, R. Brugnera, D. Budjáš, A. Caldwell, C. Cattadori, A. Chernogorov, F. Cossavella, E. V. Demidova, A. Domula, V. Egorov, R. Falkenstein, A. Ferella, K. Freund, N. Frodyma, A. Gangapshev, A. Garfagnini, C. Gotti, P. Grabmayr, V. Gurentsov, K. Gusev, K. K. Guthikonda, W. Hampel, A. Hegai, M. Heisel, S. Hemmer, G. Heusser, W. Hofmann, M. Hult, L. V. Inzhechik, L. Ioannucci, J. Janicskó Csáthy, J. Jochum, M. Junker, T. Kihm, I. V. Kirpichnikov, A. Kirsch, A. Klimenko, K. T. Knöpfle, O. Kochetov, V. N. Kornoukhov, V. V. Kuzminov, M. Laubenstein, A. Lazzaro, V. I. Lebedev, B. Lehnert, H. Y. Liao, M. Lindner, I. Lippi, X. Liu, A. Lubashevskiy, B. Lubsandorzhiev, G. Lutter, C. Macolino, A. A. Machado, B. Majorovits, W. Maneschg, M. Misiaszek, I. Nemchenok, S. Nisi, C. O'Shaughnessy, L. Pandola, K. Pelczar, G. Pessina, A. Pullia, S. Riboldi, N. Rumyantseva, C. Sada, M. Salathe, C. Schmitt, J. Schreiner, O. Schulz, B. Schwingenheuer, S. Schönert, E. Shevchik, M. Shirchenko, H. Simgen, A. Smolnikov, L. Stanco, H. Strecker, M. Tarka, C. A. Ur, A. A. Vasenko,

O. Volynets, K. von Sturm, V. Wagner, M. Walter, A. Wegmann, T. Wester, M. Wojcik, E. Yanovich, P. Zavarise, I. Zhitnikov, S. V. Zhukov, D. Zinatulina, K. Zuber, and G. Zuzel. Results on neutrinoless double-β decay of ^{76}Ge from phase i of the gerda experiment. *Phys. Rev. Lett.*, 111:122503, Sep 2013.

[22] D. Liventsev, I. Adachi, H. Aihara, K. Arinstein, D. M. Asner, V. Aulchenko, T. Aushev, A. M. Bakich, A. Bay, K. Belous, and et al. Search for heavy neutrinos at belle. *Physical Review D*, 87(7), Apr 2013.

[23] J. Dorenbosch, J.V. Allaby, U. Amaldi, G. Barbiellini, C. Berger, F. Bergsma, A. Capone, W. Flegel, L. Lanceri, M. Metcalf, C. Nieuwenhuis, J. Panman, K. Winter, I. Abt, J. Aspiazu, F.W. Büsser, H. Daumann, P.D. Gall, T. Hebbeker, F. Niebergall, P. Schütt, P. Stähelin, P. Gorbunov, E. Grigoriev, V. Kaftanov, V. Khovansky, A. Rosanov, A. Baroncelli, L. Barone, B. Borgia, C. Bosio, M. Diemoz, U. Dore, F. Ferroni, E. Longo, L. Luminari, P. Monacelli, F. De Notaristefani, P. Pistilli, R. Santacesaria, C. Santoni, L. Tortora, and V. Valente. A search for decays of heavy neutrinos in the mass range 0.5–2.8 gev. *Physics Letters B*, 166(4):473–478, 1986.

[24] Oleg Ruchayskiy and Artem Ivashko. Restrictions on the lifetime of sterile neutrinos from primordial nucleosynthesis. *Journal of Cosmology and Astroparticle Physics*, 2012(10):014–014, Oct 2012.

[25] Stefan Antusch and Oliver Fischer. Testing sterile neutrino extensions of the standard model at future lepton colliders. *Journal of High Energy Physics*, 2015(5), May 2015.

[26] G. Bernardi, G. Carugno, J. Chauveau, F. Dicarlo, M. Dris, J. Dumarchez, M. Ferro-Luzzi, J.-M. Levy, D. Lukas, J.-M. Perreau, Y. Pons, A.-M. Touchard, and F. Vannucci. Further limits on heavy neutrino couplings. *Physics Letters B*, 203(3):332–334, 1988.

[27] F. Vannucci. DECAYS AND OSCILLATIONS OF NEUTRINOS IN THE PS-191 EXPERIMENT. In *20th Rencontres de Moriond: Electroweak Interactions*, 1985.

[28] P. Abreu et al. Search for neutral heavy leptons produced in Z decays. *Z. Phys. C*, 74:57–71, 1997. [Erratum: Z.Phys.C 75, 580 (1997)].

[29] Search for displaced vertices of oppositely charged leptons from decays of long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. arXiv:1907.10037v1, 23 Jul 2019.

[30] Albert M Sirunyan et al. Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 01:122, 2019.

[31] Silvia Pascoli, Richard Ruiz, and Cedric Weiland. Heavy neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14$, 27, and 100 tev. *Journal of High Energy Physics*, 2019(6), Jun 2019.

[32] N. Aghanim et al. Planck 2018 results. VI. Cosmological parameters. *Astron. Astrophys.*, 641:A6, 2020.

[33] Laurent Canetti and Mikhail Shaposhnikov. Baryon asymmetry of the universe in the vmsm. *Journal of Cosmology and Astroparticle Physics*, 2010(09):001–001, sep 2010.

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