NEUTRINOS AND LHC PHYSICS*

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Neutrino mass models constitute well motivated scenarios of Beyond-the-Standard-Model physics. The interplay between low energy searches and high energy LHC physics provides us with an effective approach to rule out, constrain or pinpoint such models. In this report, we give a brief overview of examples where LHC searches can help to determine the mechanism of light neutrino mass generation and potentially falsify baryogenesis mechanisms.

1. Introduction

Following the discovery of the Higgs boson at the LHC and the determination of its couplings to fermions, we are close to verifying the mechanism of charged fermion mass generation. What will remain missing though is an understanding of the light neutrino masses. The observation of neutrino oscillations shows that neutrinos have finite masses and that individual lepton flavour is violated. Neutrinos are also usually considered to be Majorana particles, an assumption that facilitates an understanding of their small masses. It is natural to expect that the violation of the individual lepton flavours and, in the case of Majorana neutrinos, the total lepton number will show up in other contexts as well. This, for example, includes rare lepton flavour violating (LFV) decays of muons/taus and the total lepton number violating (LNV) neutrinoless double beta ($0\nu\beta\beta$) decay.

Quite generally, the possible violation of lepton flavour/number should be searched for at all energies that are experimentally accessible. This is because the observation of such processes would equally allow us a direct insight into the mechanism of neutrino mass generation. The most popular

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example is the so-called seesaw mechanism (of type I) in which heavy right-handed Majorana neutrinos N with masses $\gtrsim 10^{11}$ GeV are added to the Standard Model (SM). Their Yukawa coupling with the left-handed neutrinos induces the light Majorana masses of light neutrinos after electroweak (EW) symmetry breaking. This motivates the lightness of neutrinos through the breaking of lepton number symmetry at a very high scale [1].

Despite its popularity, the default type-I seesaw mechanism has two major phenomenological issues: *(i)* In the expected regime with $m_N \gtrsim 10^{11}$ GeV, the heavy neutrinos are far too heavy to be probed experimentally; *(ii)* The heavy neutrinos are sterile, *i.e.* gauge singlets and they only interact through a small mixing with light neutrinos. In this short proceedings report, we will briefly review two scenarios that instead include TeV scale and potentially non-singlet neutrinos and which can be probed at the LHC. In addition, we will comment on the general impact of the experimental observation of LNV on baryogenesis models.

2. Low scale seesaw

In the standard type-I seesaw model with the (one generation) mass matrix for the left- and right-handed neutrino,

$$\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_N \end{pmatrix}, \tag{1}$$

the mass of the light neutrino ν and its mixing θ with the heavy neutrino N is given by $m_\nu = -m_{\mathrm{D}}^2/m_N$ and $\theta = m_{\mathrm{D}}/m_N = \sqrt{m_\nu/m_N}$, respectively. Here, m_{D} is the neutrino Dirac mass, expected to be of the order of the EW scale, and m_N is an LNV Majorana mass of the right-handed neutrino. For an observed light neutrino mass scale $m_\nu \approx 0.1$ eV this yields $\theta \approx 10^{-5}\sqrt{\mathrm{GeV}/m_N}$. For a GeV to TeV scale for the heavy neutrino mass, the mixing is rather small. This will be very different in the inverse seesaw scenario [2] described by the mass matrix

$$\begin{pmatrix} 0 & m_{\mathrm{D}} & 0 \\ m_{\mathrm{D}} & \mu_{\mathrm{R}} & m_N \\ 0 & m_N & \mu_{\mathrm{S}} \end{pmatrix}, \tag{2}$$

similarly for the left-handed neutrino, the right-handed neutrino and an additional SM gauge singlet state S. Due to the presence of the small lepton number violating mass parameters μ_{R} and μ_{S}, light neutrino masses are achievable for any $\theta = m_{\mathrm{D}}/m_N$ [3]; in the simplest inverse scenario with $\mu_{\mathrm{R}} = 0$, one has $\theta \approx 10^{-2}\sqrt{\mathrm{keV}/\mu_{\mathrm{S}}}$. The reason for this suppression can be understood as the two heavy neutrino states formed by N and S have

opposite CP parities and they combine to form quasi-Dirac neutrinos with a fractional mass splitting of the order of μ_{S}/m_N. All lepton number violating observables, such as the light neutrino mass, will be suppressed by this small mass splitting.

In order to see the transition between standard and inverse seesaw, we choose $\mu_{\mathrm{S}} = \mu_{\mathrm{R}}$ in Eq. (2). Fixing the other terms as $m_N = 1$ TeV and $m_{\mathrm{D}} = 10$ GeV, Fig. 1 shows that successful light neutrino mass generation occurs for $\mu \approx 10^{-6}$ GeV corresponding to the inverse seesaw and $\mu \approx 10^{12}$ GeV corresponding to the normal high-scale seesaw. The inverse case contains two heavy Majorana neutrinos with masses $m_N \pm \mu_{\mathrm{S}}$ constituting a quasi-Dirac state, whereas for large $\mu \gg m_N$ GeV two heavy quasi-degenerate Majorana neutrinos with masses $\mu \pm m_N$ are formed.
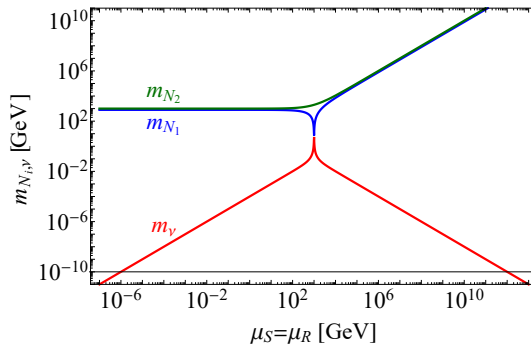

Fig. 1. Spectrum of neutrino mass eigenstates as a function of the LNV parameter $\mu_{\mathrm{S}} = \mu_{\mathrm{R}}$ with $m_N = 1$ TeV and $m_{\mathrm{D}} = 10$ GeV. The horizontal line denotes the desired light neutrino mass scale $m_\nu \approx 0.1$ eV for the lightest state.

3. Heavy sterile neutrinos

A large number of laboratory searches put constraints on the mixing between sterile and active neutrinos: For $m_N \ll 1$ MeV, sterile neutrinos are being probed in neutrino oscillation experiments. For pure Majorana sterile neutrinos, $0\nu\beta\beta$ searches provide stringent constraints on the mixing with electron neutrinos [5, 6], but these limits are considerably weakened for quasi-Dirac neutrinos such as found in the inverse seesaw mechanism discussed above. For 1 MeV $\lesssim m_N \lesssim 1$ GeV, the active-sterile mixing is constrained by peak searches in leptonic decays of pions and kaons and in beam dump experiments. A more coherent overview of experimental searches for sterile neutrinos can be found in the recent review [4].

Regarding LNV at high energy colliders, a general observation can be made in scenarios with approximately conserved lepton number like the above inverse seesaw mechanism: Like any LNV observable, the rate of an

LNV process will be suppressed by the small mass splitting, but for on-shell resonant production of a heavy neutrino, the suppression is with respect to the neutrino width, $\Delta m_N/\Gamma_N$, rather than the absolute mass or the energy scale of the process. For $\Delta m_N \approx \Gamma_N$, it can be resonantly enhanced [7]. The effect of the suppression is shown in Fig. 2 giving contours of $\Delta m_N/\Gamma_N$ as a function of the inverse seesaw parameters m_N and μ_S. Within the dark grey/red shaded region, the suppression by either the mass splitting or the active-sterile mixing $|V_{lN}|^2$ would be too severe to expect an LNV observation in the near future.
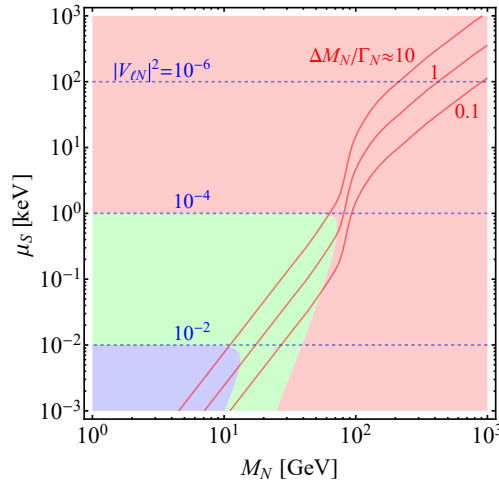

Fig. 2. Ratio of the mass splitting $\approx \mu_S$ between the sterile heavy neutrinos to their average decay width in the inverse seesaw model (solid red contours). The horizontal blue lines denote contours of constant active-sterile mixing $|V_{lN}|^2$. The shaded regions take into account the effect of both the mass and coupling suppression. The LNV signal is expected to be too small to be observed in the dark grey/red shaded region.

In the specific context of the LHC, a Majorana heavy neutrino leads to a LNV signature with two the same-sign leptons plus jets and no missing energy: $pp \to W^{(*)} \to N\ell^{\pm} \to \ell^{\pm}\ell^{\pm}jj$ [8]. The CMS and ATLAS collaborations have performed direct searches for the production of heavy neutrinos limiting the mixing to active neutrinos $|V_{e(\mu)N}|^2 \lesssim 10^{-2} - 10^{-1}$ for $m_N \lesssim 500$ GeV at $\sqrt{s} = 8$ TeV [9]. During the ongoing Run 2 of the LHC, the limits could be improved to apply to about a TeV. In addition to the basic s-channel production, it is also worthwhile to consider other production modes and decay scenarios: Electroweak t-channel processes of the form of $pp \to W^*\gamma^* \to N\ell^{\pm}jj$ can, for example, give a better sensitivity for higher m_N values. Furthermore, searches for displaced vertices can considerably improve the sensitivity for heavy neutrinos lighter than the W boson [10].

4. Left–right symmetric models

One of the simplest options to extend the above sterile neutrino scenario is an additional, broken $U(1)'$ gauge symmetry under which the heavy neutrinos are charged. Under favourable parameter conditions, heavy neutrinos can then be pair-produced abundantly and be probed even for very small mixing with the active neutrinos [11]. Another popular option are left–right symmetric models (LRSMs); the minimal LRSM extends the SM gauge symmetry to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [12]. Leptons are assigned to doublets $L = (\nu, \ell)_L$ and $R = (N, \ell)_R$ under $SU(2)_L$ and $SU(2)_R$, respectively. The Higgs sector of the minimal LRSM consists of a bidoublet and two triplets $\Delta_{L,R}$. The VEV v_R of the neutral component of Δ_R breaks the gauge symmetry $SU(2)_R \times U(1)_{B-L}$ to $U(1)_Y$ and gives masses to the RH gauge bosons W_R, Z_R and the right-handed neutrinos N. LRSMs provide a simple ultraviolet complete seesaw mechanism with the key properties built in: The presence of right-handed neutrinos is a necessary ingredient and the LNV seesaw scale can be identified with the breaking scale of the $SU(2)_R$ symmetry.

With regard to LHC searches, the right-handed current interactions in the LRSM can lead to a significant enhancement of the LNV signal. Even for negligible left–right neutrino mixing, heavy neutrinos can be directly produced via s-channel W_R exchange [13]. The potential to discover LFV and LNV at the LHC in this scenario has for example been analysed in [14]. Figure 3 compares the sensitivity of such searches with the sensitivity of $0\nu\beta\beta$ and low energy LFV experiments assuming equality of the $SU(2)_L$ and $SU(2)_R$ gauge couplings, $g_R = g_L$. In addition to right-handed currents, LNV in LRSMs may also occur through doubly-charged Higgs production or in decays of the SM-like Higgs [15].

Both ATLAS and CMS have reported excesses in searches for dibosons, dijets and $e^\pm e^\mp jj$ using the LHC Run 1 data, situated at invariant masses near 2 TeV. While far from being statistically significant, their coincidence at a resonant mass of 2 TeV is intriguing. Among several interpretations put forward in the literature, the excesses could be understood as a hint for W_R production with $m_{W_R} \approx 2$ TeV, an $SU(2)_R$ gauge coupling $g_R \approx 0.6 g_L$ and a W–W_R mixing of $\sin\theta_{LR}^W \approx 1.5 \times 10^{-3}$ [16]. Following through in this scenario, the CMS excess in $e^\pm e^\mp jj$ [17] can be tentatively interpreted as the production of a heavy, quasi-Dirac neutrino as discussed above. This would allow to connect the LHC searches with neutrino physics, specifically the heavy neutrino mass and the strength of its mixing with the light neutrinos [18], *cf.* Fig. 4.
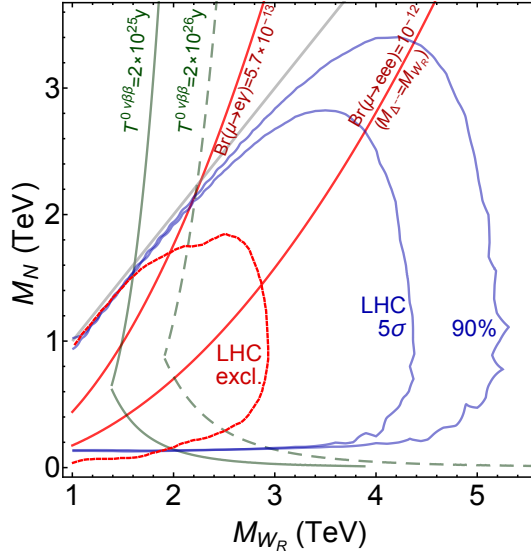
Fig. 3. Sensitivity of the LHC to production and decay of heavy neutrinos via right-handed currents in the manifest LRSM. The solid dark grey/blue contours give the signal significance of 5σ and 90% at the LHC with 14 TeV and $\mathcal{L} = 300$ fb^{-1}. The light grey/green and black/red contours show the sensitivity of $0\nu\beta\beta$ and LFV searches as denoted.
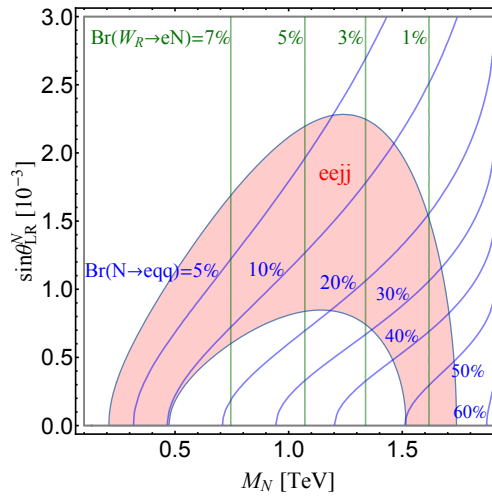

Fig. 4. Fitting the CMS $eejj$ excess (grey/red band) in the parameter plane of the heavy neutrino mass M_N and the light-heavy mixing $\sin\theta_{\mathrm{LR}}^N$. The other LRSM parameters are chosen in concordance with other excesses at 2 TeV as described in the text. Taken from [18].

5. Falsifying high-scale baryogenesis

The observed matter–antimatter asymmetry of the universe cannot be understood with SM physics. A large number of possible mechanisms to generate the observed asymmetry have been proposed in the literature. A particularly interesting scenario in our context is leptogenesis [19]. In its original formulation, the out-of-equilibrium and CP-violating decay of the heavy Majorana neutrinos in the type-I seesaw mechanism create a lepton asymmetry which is then converted into a baryon asymmetry through $(B + L)$ violating EW sphaleron processes [20].

The presence of LNV is a crucial ingredient in leptogenesis. Furthermore, the observation of LNV would have important consequences on the viability of baryogenesis models in general; specifically, it is possible to falsify a large class of high-scale baryogenesis scenarios if LNV was observed at the LHC [21]. For example, if a resonant LNV process with the signature $pp \to l^{\pm}l^{\pm}jj$ is observed, its LHC cross section σ_{LHC} is related to the induced lepton asymmetry washout rate Γ_{W}/H (relative to the expansion of the universe) [21],

$$\log_{10} \frac{\Gamma_{\mathrm{W}}}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\mathrm{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}} \,. \tag{3}$$

Here, M_X is the mass of the hypothetically observed resonance. If $\Gamma_{\mathrm{W}}/H \gg 1$, the dilution of a primordial net lepton number density, understood to be produced in a baryogenesis mechanism at a higher scale, is highly effective and the lepton asymmetry would be washed out before it can be converted by sphaleron processes. This is illustrated in Fig. 5. Observation of LNV at the LHC would therefore rule out or strongly constrain baryogenesis scenarios above the scale M_X.

A similar argument can be applied to non-standard mechanisms mediating $0\nu\beta\beta$ decay and low energy LFV processes [22]: if observed, the corresponding processes would be in equilibrium in certain temperature ranges. This is shown in Fig. 6 where the coloured bars denote the efficient equilibration temperatures assuming the relevant observable is seen at the current (left bar) or expected future (right bar) sensitivity. In the case of the 7,9,11-dimensional effective operators $\mathcal{O}_{7,9,11}$ mediating $0\nu\beta\beta$ decay, an electron–lepton asymmetry present at higher energies would be washed out. Observation of LFV via 6-dimensional LFV operators at compatible scales would allow to extend the argument to other flavours than the electron.
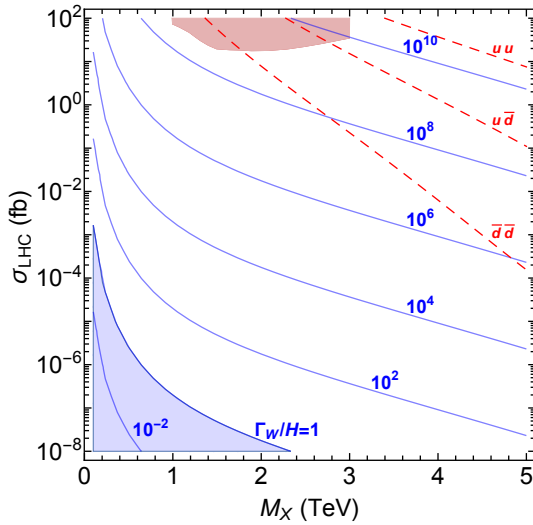
Fig. 5. Temperature intervals where the given LNV and LFV operators are in equilibrium assuming that the corresponding process is observed at the current or future experimental sensitivity. Taken from [21].
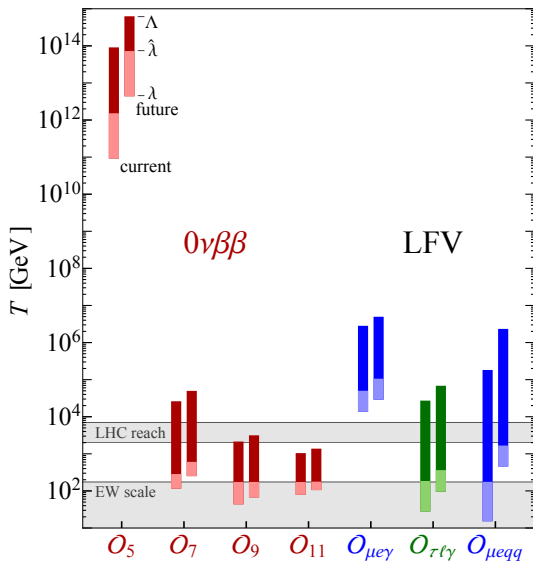

Fig. 6. Temperature intervals where the given LNV and LFV operators are in equilibrium assuming that the corresponding process is observed at the current or future experimental sensitivity. Taken from [22].

6. Conclusions

The synergy between low energy and high intensity searches on the one hand and high energy LHC searches on the other are an effective approach to rule out, constrain or ideally pinpoint such models. In this report, we have briefly reviewed a few phenomenological scenarios where the LHC can help us to find out whether the light neutrino masses (and maybe the matter–antimatter asymmetry as well) are generated in a mechanism close to the electroweak scale or beyond.

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