

Falsifying High-Scale Leptogenesis at the LHC

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Measuring a non-zero value for the cross section of any lepton number violating (LNV) process would put a strong lower limit on the washout factor for the effective lepton number density in the early universe at times close to the electroweak phase transition and thus would lead to important constraints on any high-scale model for the generation of the observed baryon asymmetry based on LNV. In particular, for leptogenesis models with masses of the right-handed neutrinos heavier than the mass scale observed at the LHC, the implied large washout factors would lead to a violation of the out-of-equilibrium condition and exponentially suppress the net lepton number produced in such leptogenesis models. We thus demonstrate that the observation of LNV processes at the LHC results in the falsification of high-scale leptogenesis models. However, no conclusions about the viability of leptogenesis models can be drawn from the non-observation of LNV processes.

INTRODUCTION

The observed baryon asymmetry of the universe (BAU), measured in terms of the baryon-to-photon number density ratio [1],

$$\eta_B^{\text{obs}} = (6.20 \pm 0.15) \times 10^{-10}, \quad (1)$$

provides evidence for physics beyond the Standard Model (SM) [2]. A popular scenario for explaining the BAU is through the mechanism of leptogenesis (LG) [3]. In the classic LG scenario, heavy right-handed neutrinos decay out of equilibrium and produce a lepton asymmetry. Necessary ingredients for this process to occur are the presence of $(B - L)$ and CP violation. The produced lepton asymmetry is then rapidly converted into the observed BAU by $(B + L)$ -violating sphaleron interactions [4].

Here, we consider lepton number violation (LNV) at the LHC through same sign dilepton signals via resonant processes of the class shown in Fig. 1. The prototype example for this signal is the resonant W_R production in left-right symmetric extensions of the SM with heavy Majorana neutrinos [5]. However, generic processes of this kind have been discussed in [6] as tree level high-energy completions of LNV operators that generate neutrinoless double beta ($0\nu\beta\beta$) decay [7]. For a recent review on $0\nu\beta\beta$ decay see, for example [8]. In Fig. 1, the intermediate particles are different vector or scalar bosons X and $Y^{(\prime)}$ and a fermion Ψ . They decay to a final state with four SM fermions composed of two quarks and two same sign charged leptons through unspecified interactions of strengths g_i ($i = 1, 2, 3, 4$). In the general case, any combination of quark/anti-quark pairs u and d in the initial state can be realized, and any two of the four final states f_i can be leptons. Note that $0\nu\beta\beta$ constrains only final states with first generation leptons, but at the LHC one could observe LNV in both electrons and muons.

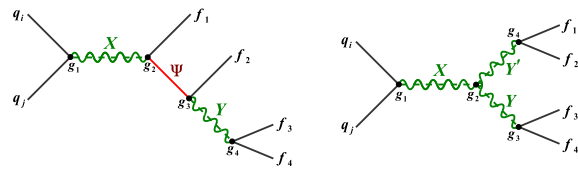


FIG. 1: Possible diagrams contributing to the resonant same sign dilepton signal $pp \rightarrow l^\pm l^\pm qq$ at the LHC. The intermediate particles X and $Y^{(\prime)}$ denote different vector or scalar bosons, Ψ indicates a fermion. In the general case [6, 7], any two of the four fermions f_i can be leptons.

In this paper, we explore the consequences of the observation of LNV processes at the LHC on the viability of LG mechanisms. Specifically, we discuss the impact of the observation of LNV at the LHC on the rate of $\Delta L = 2$ scattering processes. As we will demonstrate, an observed non-zero cross section can be converted into a lower limit on the washout of the lepton asymmetry in the early universe. If the primordial lepton number asymmetry is originally generated above the LNV scale observed at the LHC, the resulting washout will reduce the asymmetry exponentially, rendering LG ineffective.

We note that the question of falsifying LG at the LHC has been investigated previously in reference [9] within the context of the minimal left-right symmetric model. Our analysis focuses instead on a model-independent approach in which we will derive general limits from the hypothetical observation of the process $pp \rightarrow l^\pm l^\pm qq$.

SAME SIGN DILEPTONS AT THE LHC

Within the $\Delta L = 2$ resonant processes of the form $pp \rightarrow l^\pm l^\pm qq$, we focus on the s-channel diagrams producing a scalar or vector boson X resonantly which then

cascade decays to the final state $l^\pm l^\pm qq$ through on- or off-shell decays. The parton level cross section can be approximated by a Breit-Wigner resonance

$$\sigma(Q^2) = \frac{4\pi}{9}(2J_X + 1) \frac{\Gamma(X \rightarrow q_1 q_2) \Gamma(X \rightarrow 4f)}{(Q^2 - M_X^2)^2 + M_X^2 \Gamma_X^2}, \quad (2)$$

with J_X being the spin of the produced boson and q_i indicating the initial partons. The partial decay width $\Gamma(X \rightarrow 4f)$ describes the complete decay of X as shown in Fig. 1. Integrating over the parton distribution functions (PDFs) in narrow-width approximation of the resonance (2) yields the total LHC cross section [10]

$$\begin{aligned} \sigma_{\text{LHC}} &= \frac{4\pi^2}{9s}(2J_X + 1) \frac{\Gamma_X}{M_X} f_{q_1 q_2} \left(\frac{M_X}{\sqrt{s}}, M_X^2 \right) \\ &\times \text{Br}(X \rightarrow q_1 q_2) \text{Br}(X \rightarrow 4f), \end{aligned} \quad (3)$$

with the LHC center of mass energy $\sqrt{s} = 14$ TeV and

$$\begin{aligned} f_{q_1 q_2}(r, M^2) &= \int_{r^2}^1 \frac{dx}{x} (q_1(x, M^2) q_2(r^2/x, M^2) + \\ & q_2(x, M^2) q_1(r^2/x, M^2)). \end{aligned} \quad (4)$$

Here, $q_i(x, Q^2)$ is the PDF of parton q_i at momentum fraction x and momentum transfer Q^2 . For masses $M \approx 1 - 5$ TeV, this integral can be well approximated as exponentially decreasing with M/\sqrt{s} [10],

$$f_{q_1 q_2} \left(\frac{M}{\sqrt{s}} \right) \approx A_{q_1 q_2} \times \exp \left(-C_{q_1 q_2} \frac{M}{\sqrt{s}} \right), \quad (5)$$

where the coefficients A_{qq} and C_{qq} depend on the combination of the relevant partons q_1, q_2 , ranging between $A_{u\bar{u}} \approx 200$ to $A_{uu} \approx 4400$ and $C_{uu} \approx 26$ to $C_{d\bar{d}} \approx 51$.

LEPTOGENESIS

The relevant Boltzmann equations for leptogenesis can be generically written in terms of the heavy neutrino and $(B - L)$ number densities per co-moving volume [11] as function of its decay rate Γ_D , the CP asymmetry ϵ and the scattering rate Γ_W , which contains inverse N decays as well as any other $\Delta L = 1, 2$ processes.

The scattering rate Γ_W induced by the process $qq \leftrightarrow l^\pm l^\pm qq$ is calculated from the reaction density [11]

$$\gamma(qq \leftrightarrow l^\pm l^\pm qq) = \frac{T}{32\pi^4} \int_0^\infty ds s^{3/2} \sigma(s) K_1 \left(\frac{\sqrt{s}}{T} \right), \quad (6)$$

with the n th-order modified Bessel function $K_n(x)$. Here, the process cross section is not averaged over the initial particle quantum numbers. Based on the same underlying process, the washout rate $\Gamma_W/H = (\gamma/n_\gamma)/H$ and the LHC cross section σ_{LHC} are directly related. The equilibrium photon density $n_\gamma \approx 2T^3/\pi^2$ and the Hubble parameter $H \approx 1.66\sqrt{g_*}T^2/M_{\text{P}}$ are temperature dependent, with the effective number of relativistic degrees

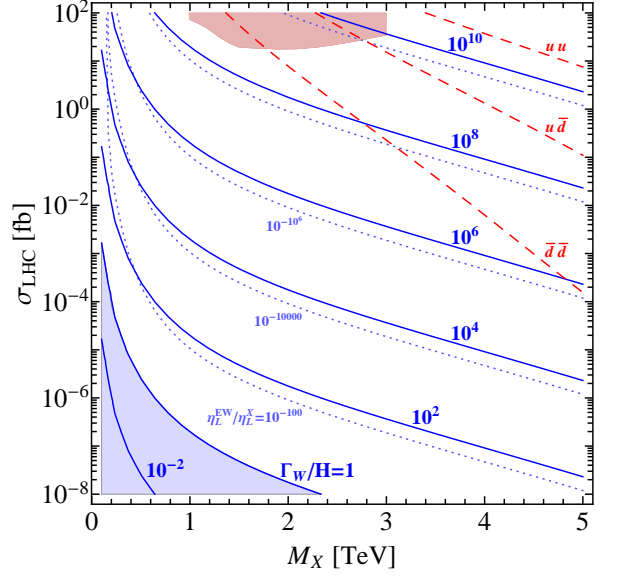


FIG. 2: Washout rate Γ_W/H at $T = M_X$ as a function of M_X and σ_{LHC} (solid blue contours). The dotted light blue contours denote the surviving lepton asymmetry at the EW scale relative to its value at M_X , $\eta_L^{\text{EW}}/\eta_L^X$. The red dashed curves are typical cross sections of the process $pp \rightarrow l^\pm l^\pm qq$. The red shaded region at the top is excluded due to recent searches for resonant same sign dileptons at the LHC [12].

of freedom g_* (≈ 107 in the SM) and the Planck mass $M_{\text{P}} = 1.2 \times 10^{19}$ GeV. This results in

$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}} \frac{M_{\text{P}} M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\sigma_{\text{LHC}}), \quad (7)$$

a relation independent of the branching ratios of the particle X and therefore valid for all coupling strengths g_i and also independent of the potential presence of other, lepton number conserving decay modes. Evaluated at $T = M_X$, i.e. the approximate onset of the washout process, Eq. (7) yields the order of magnitude estimation

$$\log_{10} \frac{\Gamma_W}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\text{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}, \quad (8)$$

using the conservative values $A_{qq} = 5000$ and $C_{qq} = 26$ for Eq. (5). From this approximation alone it is clear that the observation of the resonant process $pp \rightarrow l^\pm l^\pm qq$ at the LHC corresponds to a very strong washout of the lepton asymmetry in the early universe. For example, the observation of a resonance at $M_X \approx 2$ TeV with a cross section $\sigma_{\text{LHC}} \approx 1$ fb corresponds to $\Gamma_W/H \approx 3 \times 10^7$. The exact relation (7) is shown in Fig. 2, based on the smallest washout among all parton combinations. For any realistic cross section observable at the LHC with $\sigma_{\text{LHC}} \gtrsim 10^{-2}$ fb, the resulting lepton number washout in the early universe is always highly effective ($\Gamma_W/H \gg 1$). The dashed curves, for example, show

typical cross sections for different parton combinations in the case of a particle X with gauge-strength total width, $\Gamma_X/M_X = g^2/(32\pi)$, with $g = 0.5$ and branching ratios $\text{Br}(X \rightarrow q_1 q_2) = \text{Br}(X \rightarrow 4f) = 0.5$. Without a source regenerating the lepton asymmetry below M_X , the washout leads to an exponential suppression of the surviving asymmetry at the EW scale compared to the value present at M_X , $\eta_L^{\text{EW}}/\eta_L^X \approx \exp(-\Gamma_W/H)$. This suppression is also shown in Fig. 2, highlighting that the observation of LNV processes at the level $\sigma_{\text{LHC}} \gtrsim 10^{-2}$ fb would necessarily result in an enormous washout of any pre-existing lepton asymmetry.

It should be stressed again that the above analysis is highly model independent and purely based on the observables M_X and σ_{LHC} of the process. The approximations used in our calculation, such as the narrow-width resonance assumption, are not expected to change this conclusion in any way. In fact, the direct relation between the LHC cross section and the washout rate is expected to hold for any LNV process, with a proportionality only affected by the kinematics of the process.

In order to further assess the impact of the resulting washout, we calculate the baryon asymmetry in the standard LG scenario with one heavy neutrino N , neglecting all other washout reactions. The Boltzmann equations in this case are most compactly expressed in terms of the out-of-equilibrium heavy Majorana neutrino density deviation $\delta\eta_N = \eta_N/\eta_N^{\text{eq}} - 1$ and the lepton density $\eta_L = n_L/n_\gamma$ normalized to the photon density n_γ [13],

$$\frac{d\delta\eta_N}{dz} = \frac{K_1(r_N z)}{K_2(r_N z)} \left[r_N + (1 - r_N^2 K_D z) \delta\eta_N \right], \quad (9)$$

$$\frac{d\eta_L}{dz} = \epsilon K_D r_N^4 z^3 K_1(r_N z) \delta\eta_N - K_W z^3 K_1(z) \eta_L, \quad (10)$$

with the decay factor $K_D = \Gamma_D/H$ at $T = M_N$ and the washout factor $K_W = \Gamma_W/H$ at $T = M_X$. We define the evolution parameter $z = M_X/T$. The above Boltzmann equations explicitly contain the full temperature (z) dependence with the hierarchy between the masses of N and X given by $r_N = M_N/M_X$. Note that Eqs. (9) and (10) implicitly assume that the CP asymmetry is generated from the decay of the heavy neutrino. Other mechanisms will yield similar results.

Fig. 3 shows a typical solution to the Boltzmann equations (9) and (10) with $M_N = 1.5$ TeV, $M_X = 2$ TeV, CP asymmetry $\epsilon = 10^{-2}$, $K_D = 10^8$, and $K_W \approx 6 \times 10^6$ (smallest washout corresponding to $\sigma_{\text{LHC}} = 0.1$ fb). For sufficiently strong rates K_D and K_W , the linear drop-off behaviour depicted can be approximated as $\delta\eta_N = 1/(r_N K_D z)$ and $\eta_L = r_N^2 \epsilon / (K_W z)$, respectively, in which case η_L is generally independent of K_D [13]. For $M_N = M_X$, η_L will eventually freeze-out to a constant value, but for a different hierarchy, the contributions to η_L depend differently on the temperature. In the case $r_N < 1$, shown in the figure, heavy neutrino decays can not be compensated by the washout for $z > 1$, whereas for $r_N >$

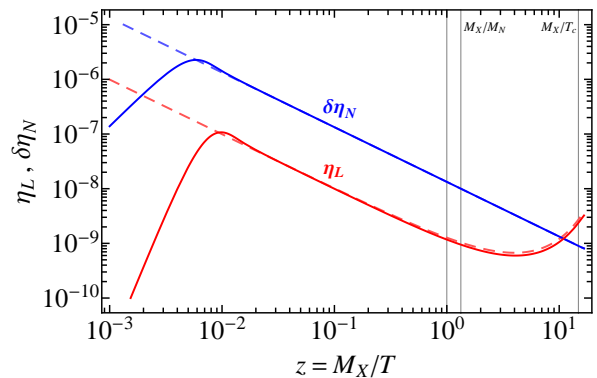


FIG. 3: Solution to the Boltzmann equations for $M_N = 1.5$ TeV, $M_X = 2$ TeV, CP asymmetry $\epsilon = 10^{-2}$, $K_D = 10^8$ and $K_W \approx 6 \times 10^6$ (smallest washout corresponding to $\sigma_{\text{LHC}} = 0.1$ fb). The dashed lines denote approximated solutions discussed in the text.

1 the washout is always effective for $z > 1$ leading to an over-proportional drop-off. The general behaviour can be well approximated by $\eta_L \approx r_N^2 \epsilon / (K_W z) \exp((1 - r_N z))$. In Fig. 3, this approximation is shown as a red dashed curve. Such a behaviour is not realistic in a given model where other processes are expected to contribute, but allows to draw model-independent conclusions. Most importantly we neglect washout from processes mediated by the heavy neutrino driven by the same interaction(s) that generate the lepton asymmetry. Taking into account all washout processes in a consistent fashion will guarantee a well-behaved freeze-out behaviour for η_L . In this spirit, our solution for η_L can be considered as a conservative, model-independent but also possibly weak upper limit on the generated lepton asymmetry.

The conversion of the lepton number to the final baryon asymmetry can be calculated by $\eta_B = -d_{\text{rec}} r_{B/L} \eta_L(T_c)$ with $r_{B/L} = (8N_g + 4N_H)/(14N_g + 9N_H) \approx 1/2$ in a general theory with N_g fermion generations and N_H Higgs doublets [14]. The critical temperature of the electroweak phase transition is denoted by $T_c \approx 135$ GeV, $d_{\text{rec}} \approx 1/27$ (in the SM) describes the increase of the photon density during the recombination epoch, and $\eta_L(T_c)$ is the lepton asymmetry at the sphaleron decoupling temperature. For details see [15].

We arrive at an upper limit for the baryon asymmetry,

$$|\eta_B| \lesssim \frac{M_N^2}{M_X^2} \frac{T_c}{M_X} \frac{r_{B/L} d_{\text{rec}} |\epsilon|}{K_W(M_X, \sigma_{\text{LHC}})} e^{(M_X - M_N)/T_c} \quad (11)$$

that can be compared to the observed value (1). By using the derived approximation (8), we can set an upper limit on the baryon asymmetry as a function of the LG parameters m_N and ϵ , and the observables M_X and σ_{LHC}

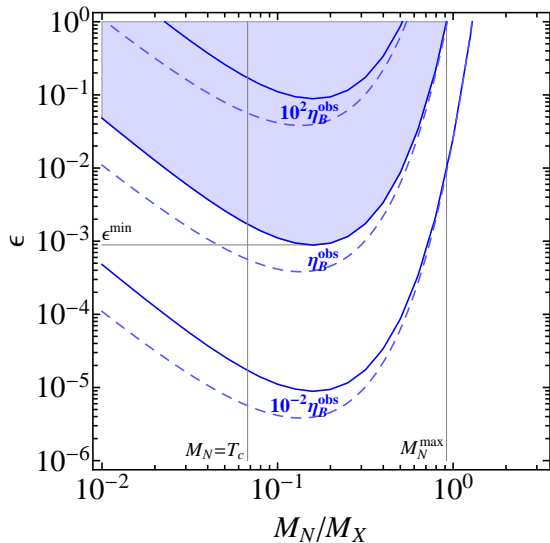


FIG. 4: Baryon asymmetry η_B as a function of M_N/M_X and ϵ for $M_X = 2$ TeV and $\sigma_{\text{LHC}} = 0.1$ fb (solid contours). The intermediate contour corresponds to the observed value η_B^{obs} , the other two contours give 100 times higher and lower values, respectively. Correspondingly, the dashed contours are determined using the approximation Eq. (11).

of the LHC process,

$$\log_{10} \left| \frac{\eta_B}{\eta_B^{\text{obs}}} \right| \lesssim 2.4 \frac{M_X}{\text{TeV}} \left(1 - \frac{4}{3} \frac{M_N}{M_X} \right) + \log_{10} \left[|\epsilon| \left(\frac{\sigma_{\text{LHC}}}{\text{fb}} \right)^{-1} \left(\frac{4}{3} \frac{M_N}{M_X} \right)^2 \right]. \quad (12)$$

In Fig. 4 the resulting baryon asymmetry for both the exact solution of the Boltzmann equations (solid line) as well as the approximation (1) (dashed line) is shown as a function of $r_N = M_N/M_X$ and ϵ for $M_X = 2$ TeV and $\sigma_{\text{LHC}} = 0.1$ fb. Two important conclusions can be drawn: (i) For $M_N > M_N^{\text{max}} \approx M_X$ it is not possible to generate a large enough baryon asymmetry. As our calculation gives a conservative upper limit for η_B , this means that the observation of the LNV process at the LHC excludes high energy LG models. (ii) For $M_N < M_X$ there exists a lower limit on the CP asymmetry $\epsilon > \epsilon^{\text{min}} \approx 10^{-3}$, which strongly constrains resonant LG models.

DISCUSSION AND CONCLUSIONS

We have discussed the impact of a possible observation of lepton number violation at the LHC on leptogenesis. We have shown that for right-handed neutrinos heavier than the mass scale at which LNV is observed at the LHC, the resulting washout factor will reduce any pre-existing lepton asymmetry L exponentially, rendering LG ineffective. Our arguments should be generally valid and

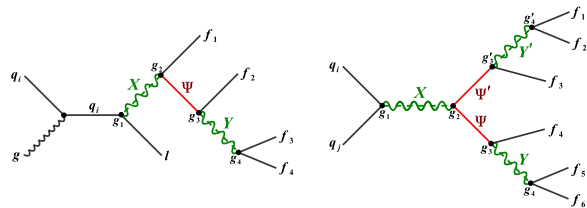


FIG. 5: Further example diagrams for different LNV process classes at the LHC with 5 (left) and 6 (right) final state particles. Note that in the latter case, in addition to the qq initial state shown, also gluon-gluon initial state diagrams can exist.

not depend on the particular realization of LG, although we have concentrated on the “standard” scenario with right-handed neutrinos. Thus, high-scale thermal leptogenesis models can be falsified in case of the observation of LNV processes at the LHC. However, it should be stressed that no conclusions about the viability of LG can be drawn from the non-observation of these processes.

There are a few possible caveats to consider: (i) One could imagine a situation where LNV is generated in the early universe in the third family only. As there is no experimental proof so far that $e^\pm e^\pm \leftrightarrow \tau^\pm \tau^\pm$ was in equilibrium in the early universe, the observation of LNV at the LHC for only e and/or μ is not sufficient in this case. A non-zero observation of $pp \rightarrow l^\pm l^\pm qq$ for either $ll = ee, \mu\mu$ and $\tau\tau$, or for $e\mu$ and $e(\mu)\tau$ is necessary to unambiguously falsify LG models in the way presented. (ii) Our discussion leaves open the possibility of LG with $M_N < M_X$. Resonant sub-TeV scale LG with large CP asymmetry ϵ , for example, would still be possible. This loophole is not limited to the classical LG with right-handed neutrinos. In general, any mechanism producing a “hidden” lepton number which is converted to B below M_X , would not be ruled out. Nevertheless, it is still possible to derive a large model-independent lower limit on the required CP asymmetry. (iii) SM sphaleron processes only affect electroweak fermion doublets, but left- and right-handed fermions are in thermal equilibrium around the electroweak scale for Yukawa couplings larger than $\approx 10^{-8}$. This is the case for all charged leptons. Our conclusions therefore also apply if the LNV process at the LHC involves right-handed leptons.

Finally, although we concentrated on the resonant process of Fig. 1, we believe our argumentation can be easily adapted to other cases. For example, leptoquark production can occur as in Fig. 5 (left) and pair production of heavy states as in Fig. 5 (right). We conjecture that our relation between the observation of the LNV at LHC and the lower limit on the washout factor is valid for these cases too, most likely even with larger numerical factors. The discovery of LNV at the LHC could then have profound implications, especially if combined with the observation of $0\nu\beta\beta$ decay at a rate expected from a short range operator induced by a process as in Fig. 1. Such

an experimental scenario would dis-favour the standard high scale seesaw mechanism as both leptogenesis and the dominance of light Majorana neutrinos mediating $0\nu\beta\beta$ decay are rendered ineffective.

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