INTURN 24-9: Lepton Number Violation and the Baryon Asymmetry of the Universe

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Abstract

In order to better understand how leptogenesis could account for the observed baryon asymmetry in the universe, it is essential to explore lepton number violating (LNV) physics. Our focus is on TeV scale LNV, where washout processes may be weak enough for standard thermal leptogenesis to remain viable. Specifically, we study the low-coupling regime, where LNV particles may be long lived. We use the simplified model introduced in Ref. [1] and expand on the analysis in Ref. [2], particularly their production of exclusion plots (e.g., Figure 3 in Ref. [2]). In attempting to reproduce their exclusion plot using only an equation for probability, we find that though a high probability is a necessary condition it is not sufficient, and the full calculation for the number of events is necessary to decisively exclude a region. However, we find that the probability function provides a reliable indicator of general exclusion regions, making it a useful preliminary tool for exploring new parameter spaces of mass and coupling. Initial results suggest that the highest probabilities do not align with the low-coupling region, though this area cannot be dismissed until the complete event calculation is performed. The authors of Ref. [2] provided the Mathematica package ManeParse [3] used for the figures in their paper, which we will use to recreate their exclusion region and, subsequently, to generate our own exclusion plot using updated mass and coupling values. Should our plot indicate that long-lived particles (LLPs) with TeV-scale masses and couplings near 10^{-6} are viable, they may offer a mechanism for generating the universe's baryon asymmetry.

1 Introduction

The baryon asymmetry problem arises from seeking to explain how the universe arrived at the current imbalance in the number of baryons over anti-baryons (often referred to as matter-antimatter asymmetry). There are many cosmological and astrophysical observations and measurements that support the claim that our universe was initially symmetric, thus we must somehow have dynamically generated this asymmetry. Whether it occurs in an instant or over an extended period of time, any theoretical process that creates the asymmetry is known as baryogenesis.

In order for any theory to be a viable explanation for baryogenesis, it must satisfy the three conditions proposed by Andrei Sakharov [4]:

1. Baryon number B violation.
2. C and CP symmetry violation.
3. Interactions out of thermodynamic equilibrium.

Baryon number violation is necessary in order for the number of baryons in the universe to have changed over time. If baryon number violation is forbidden, then reactions that produce more baryons than anti-baryons cannot occur. The second condition ensures that interactions creating baryons proceed at different rates than those creating antibaryons. Similarly, if the third condition was not satisfied and an overdensity in baryons was generated in thermal equilibrium, then it would be quickly smoothed out.

Theoretically, the Standard Model (SM) contains all the necessary building blocks to satisfy these conditions. However, the C- and CP-symmetry violating terms within the SM could not generate the presently observed asymmetry, and there's no out-of-equilibrium phase transition for the Higgs boson mass [5]. While some take this as an argument against baryogenesis, we see it as a confirmation that the Standard Model is not sufficient to explain the physics of our universe. This statement is reinforced by recent breakthroughs in physics, including the measurement of a nonzero neutrino mass.

In a way, the neutrino mass has long indicated that we need to move beyond the current SM. The SM dictates that since there is no right-handed counterpart of the neutrino to acquire mass via the Higgs mechanism, the neutrino should be a massless particle. However, oscillation experiments have demonstrated that neutrinos have a tiny mass, definitively proving the Standard Model insufficient. To explain not only the mass of the neutrino, but the lightness of it, a theory known as the Seesaw Mechanism proposes that a very massive RH neutrino exists [6]. Not only does this mechanism explain the mass of the neutrino, it also gives insight into the identity of the neutrino as a Dirac or Majorana mass particle.

In order for the Seesaw Mechanism to be viable, the neutrino must be a Majorana mass particle, meaning that it is its own antiparticle. Confirming this would lead to a groundbreaking frontier in physics, one where lepton number violation (LNV) is not forbidden. For example, in addition to the well known double beta decay, LNV allows neutrinoless double beta decay ($0\nu\beta\beta$) to exist in nature. The two neutrinos that are produced in regular beta decay become internal as they are each other's antiparticle, leaving a process with two leptons where it started with none. Not only is this exciting because we learn more about a very fundamental particle, it also opens the door to a new theory for generating baryon asymmetry through a process called leptogenesis.

Leptogenesis is the term for any process that first generates an excess in lepton number, which is then by various mechanisms transformed into an excess in baryon number. It requires all three conditions that need to be met for baryogenesis, and the additional condition of lepton number violation. The first version of leptogenesis was proposed in a paper by Fukugita and Yanagida in 1986, and they used the Majorana mass neutrino to generate the over-density in leptons [7]. It is a favorable theory because it does not require a grand unified theory (GUT) [7], and there are already experiments underway (such as the search for $0\nu\beta\beta$ decay) whose success would serve as evidence [8]. So, from the intangible reaches of baryogenesis in the early universe, leptogenesis gives us a theory that could be testable using similar methods to those currently in use at the Large Hadron Collider (LHC).

However, this theory has its drawbacks because of the heaviness required for the RH neutrino. Following the Seesaw Mechanism, it predicts that the RH neutrino would be on the order of 10^{10} GeV compared to the LH mass of around 10^{-10} GeV. So, while leptogenesis through the decay of the heavy neutrino works well in theory, this energy scale is out of reach for the currect colliders. Additionally, for certain lepton number violating processes, the interaction strength may be too strong and actually wash out the asymmetry.

So, there are two paths to take from this point: build more powerful machinery, or look for LNV at different energy scales. The former requires incredible amounts of time, energy, and grant-writing. Although this is inherent to nuclear research, this theory has the additional caveat of washout at these higher coupling strengths. If we follow the latter, we could explore novel areas of beyond Standard Model (BSM) physics in the smaller coupling regions where leptogenesis is potentially still viable via RH neutrino decay (also known as standard thermal leptogenesis). This is the path that my project follows, with the choice of energy scale and model used reflecting the work done in references [8] and [2].

Now that we have a tighter grasp on what energy scale to look for LNV, we need to think about what it could possible look like and how we could detect it. One theory, and the one that my project focuses on, is the potential for these weakly interacting particles to be long lived. If this were the case, then as we shift towards lower couplings we should be able to detect these particles so long as we move the detector further away from the interaction point. This is the proposition for building the new detector MATHULSA in the LHC [9]. MATHULSA would be located with its front end at a distance of $L_1 = 200$ m away from the LHC interaction point and the back end at a distance of $L_2 = 230$ meters, far more optimized for searching for LLPs [9].

It's important for us to better understand the coupling strength region where these particles could live, because this allows us to predict where we could detect them. Most searches have anticipated the decay of particles to be prompt within the closest detectors, yet there could be ground breaking physics just 200 meters away. If we observe these particles exhibiting LNV within a certain coupling strength region, it could be the key to understanding the mechanism for leptogenesis and explaining the baryon asymmetry of our universe.

1.1 The O2 Model

The previous discussion motivates our work in exploring the low coupling region, but there are still nearly infinite possibilities for what LNV LLPs could look like. In order to meaningfully analyze how coupling strength and mass levels impact LLP decay we use a simplified framework, the O2 Model, which adds a limited number of particles and interactions alongside those in the SM [10]. This model includes three new particles, whose properties are listed in Table 1, and has five relevant parameters, listed in Table 2. Limiting ourselves to just these additions allows us to make concrete calculations for chosen input parameters. Readers can refer to reference [8] and [10] for a more in depth explanation of the choices made when developing this model.

New Particle	S_0	$S_\pm$	F
Spin	Scalar (0)	Scalar (0)	Majorana fermion (1/2)
Charge	Neutral	$+/-$	Neutral
Antiparticle	Itself	$S_\mp$	Itself

Table 1: O2 Model Particle Properties

Parameter	O2 Model Description	Use in our project
g_{qu}	Yukawa coupling for Q − S − u interaction	Set to zero
g_{qd}	Yukawa coupling for Q − S − d interaction	Varied
g_e	Yukawa coupling for L − S − F interaction	Varied
m_s	Mass of S_0 = mass of $S_\pm$	TeV scale
m_f	Mass of F	TeV scale

Table 2: O2 Model Parameters

Table 1 provides the properties of the three new particles in the model, with the choice of F being a Majorana fermion reflecting the earlier discussion. In table 2 we note that g_{qu} is set to zero for simplification, which allows us to highlight g_{qd} and g_e as the primary variables. This project is structured by individual cases, where each case has fixed TeV-scale masses for m_s and m_f, respectively[1]. We vary the coupling constants across a grid of values ranging from 10^{-7} to 10^{1}. This broad range for coupling strength helps us verify the location of highest probability, and whether this lands within the desired range of 10^{-7} to 10^{-6}. As previously discussed, the choice of TeV-scale masses is motivated by the need for a lower energy scale, detailed in references [5] and [8]. If we detect long-lived particles at this scale and with sufficiently low couplings, these particles could become viable candidates for generating leptogenesis, and further our understanding of LNV physics and the origin of the baryon asymmetry of our universe.

2 Results and Discussion

Although there are existing methods to search for LLPs using current ATLAS/CMS detectors [11], these systems encounter challenges due to trigger and background obstacles that prevent their optimization for LLP detection [9]. The proposed MATHULSA detector would be located further away, and would be better suited for the purpose of LLP searches. Our current work furthers our understanding of how low coupling, TeV scale LLPs could be detected within this new detector. Specifically, we aim to determine how the probability of detecting LLPs within MATHULSA varies for different coupling strengths and mass levels.

To achieve this, we use the equations from reference [2] to relate coupling strength to the decay length of a LLP for a set of given parameters. This enables us to solve equation 1, the probability that a LLP will decay inside of a detector a distance from the LHC interaction point, as a function of coupling strength. Since coupling strength is our primary focus, this approach allows for straightforward and efficient comparisons.

[1]To align with the equations from reference [2], we follow their restriction of $m_s > m_f$ to ensure the validity of the relationships used.

However, relying solely on the probability may not the be most rigorous method for understanding whether a certain coupling could produce the LNV LLP we hope to detect. In reference [2], the authors performed a detailed analytical calculation to determine which coupling regions could meet the 95% confidence limit of $N_{obs} = 3$. [2] Using the Mathematica package, ManeParse[3] [3], they calculate each element[4] in equation 2, and determine the coupling regions that reach the confidence level expected for MATHULSA. Their plot shows that for $m_S = 2$ TeV and $m_F = 10$ GeV, the exclusion limits for coupling strength for MATHULSA fall in the range of 10^{-1} to 10^{1}. Although this is higher than the coupling strengths we are interested in, this plot provides valuable insight into the magntiude with which the probability impacts the calculation of the number of events.

$$P_{decay} = e^{-L_1/d} - e^{-L_2/d} \tag{1}$$

$$N_{obs}^{MATH} = \sigma_{eF}\; Br_{ejj}\; \mathcal{L}\; \epsilon_{LLP}^{MATH}\; \epsilon_{geometric}\; P_{decay} \tag{2}$$

$$d = \frac{1}{1+\Delta_{QCD}} \frac{1024\pi^3 \hbar c}{3} \frac{m_s^5}{m_F^6} (\frac{1}{g_l g_q})^2 \tag{3}$$

We are especially interested in the probability equation because of its utility when we substitute in equation 3 for d, the boosted decay length of a LLP. As discussed in section 1.1, for each case we select specific values for the masses and vary the couplings over a wide range. Since all other parameters are constants [5], we obtain an equation that describes the likelihood of a LLP decaying within MATHULSA as a function of coupling strength.

Given the simplicity of this relationship, it would be convenient to be able to use the probability to definitively say whether or not a set of couplings and masses could meet the required $N_{obs} = 3$ requirement in order to be a viable candidate for LNV LLP detectable in MATHULSA. To assess the effectiveness of this approach, we sought to reproduce the exclusion plot from reference [2].

Our goal was to verify if we could replicate the exclusion plot for reference [2] using only the probability equation and match the MATHULSA region accurately. If successful, this would indicate that the probability is the strongest factor in determining the number of events, allowing us to bypass the need for the full N_{obs} calculation for every parameter change. This would greatly expedite the process of scanning over different masses and coupling strengths.

To recreate the plot from reference [2], I used a python notebook with the probability function (integration equations 1 and 3), and generated the countour plot in figure 1. The colorbar on the right indicates how the probability varies with coupling, with yellow representing the highest probability. The shape of the red oval comes from the limits from the exclusion plot from reference [2]. While the region of highest probability does overlap with the exclusion bounds from that plot, it extends beyond these bounds as well. This suggests that while a high probability is necessary for meeting the event criteria, it is not the sole determining factor.

[2] This value was obtained by assuming zero background, more information on this choice can be found in Ref.[12]

[3] ManeParse is a self-contained package that enables the use of Mathematica for calculations involving Parton Distribution Functions and more, the details of which are discussed in reference [3]

[4] σ_{eF} is the total cross section of processes $pp --> e^+F$ and $pp --> e^-F$. The geometric acceptance for MATHULSA,$\epsilon_{geometric}$, is a constant 0.05. The detection efficiency per decay ϵ_{LLP}^{MATH} changes for different decays. The luminosity for MATHULSA is $\mathcal{L} \simeq 3$. The branching ratio must be calculated per interaction.

[5] With the slight exception of Δ_{QCD} which is a function of m_F. However, as we fix m_F case by case, Δ_{QCD} also becomes fixed, and we track its variation with mass. Further details are available in reference [2].

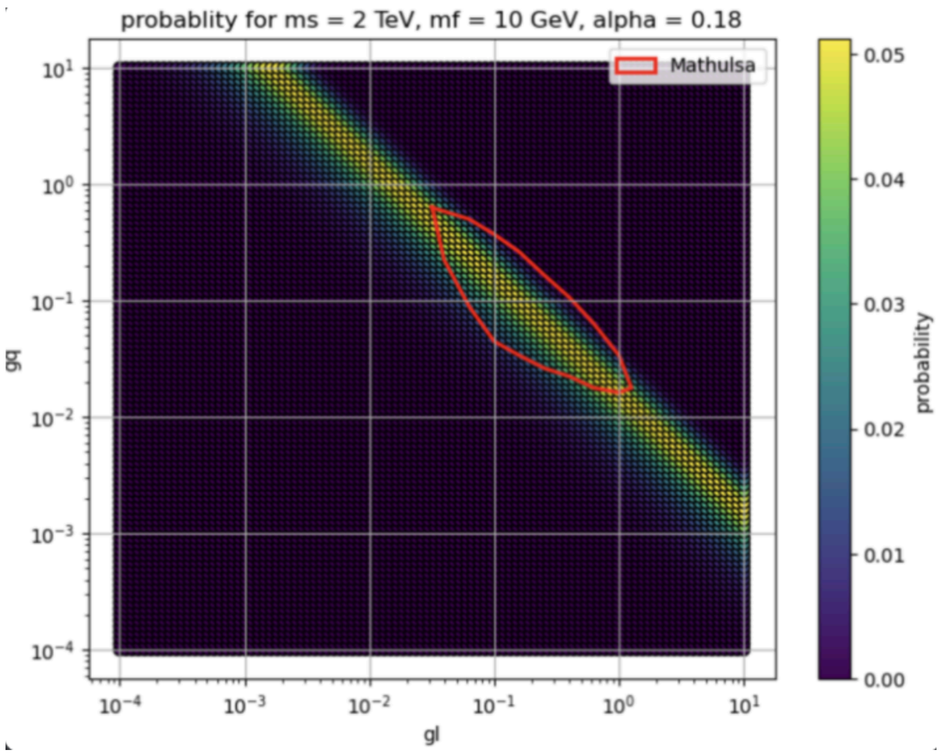

Figure 1: The probability of detecting a LLP within the MATHULSA detector as a function of coupling strengths $g_l = g_e$ and $g_q = g_{qd}$. The red oval represents the bounds of the exclusion region represented in Figure 3 of reference [2].

Thus, while the probability is a strong indicator of which coupling regions are likely to meet the criteria for the number of events, a full calculation accounting for all relevant factors of N_{obs}, is necessary to draw definitive conclusions. Further details on how plan to procees with this calculation are provided in section 3.

However, given that the probability provides a useful preliminary indicator, we can use it as a starting point to identify which combinations of couplings and mass levels are most promising. As discussed earlier, we are particularly interested in TeV scale masses with couplings around 10^{-6} or 10^{-7}, as these combinations are expected to be able to produce lepotgenesis without significant washout. We used the same python notebook to analzyze this range of masses/couplings to determine where the highest probabilities occur, resulting in Figures 2-4.

These figures show which coupling pairs produce the highest probability for being detected within the MATHULSA detector. We hoped to see that for any TeV scale masses, the highest probability would be near the 10^{-6} range where the particles are likely long lived. We see that when the two masses are similar in magnitude, the region of highest probability approaches the 10^{-1} coupling region, but when there is a large difference it quickly moves towards the higher coupling values. Either way, none of these results truly reach the coupling region that we need in order for these particles to be a viable LLP candidate for leptogenesis.

However, as we discussed earlier, we know that the probability is not sufficient to independently determine whether or not a certain coupling region are viable. Though the results of these graphs are not promising, the full calculation for the number of events is required to truly exclude TeV scale LLPs from being a mechanism for producing leptogenesis.

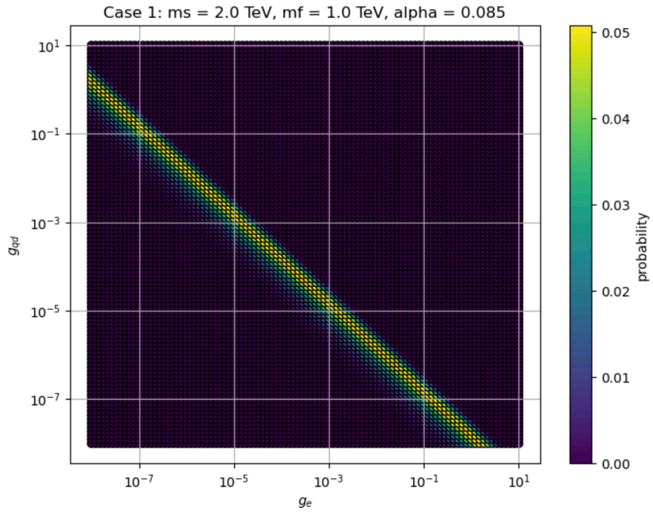

Figure 2

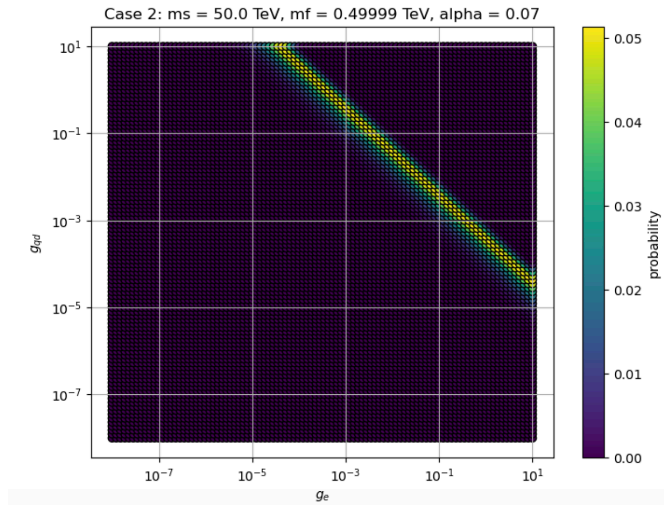

Figure 3

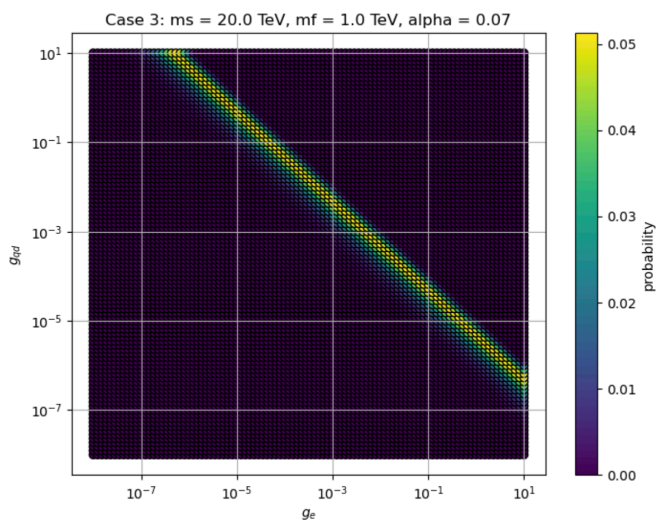

Figure 4

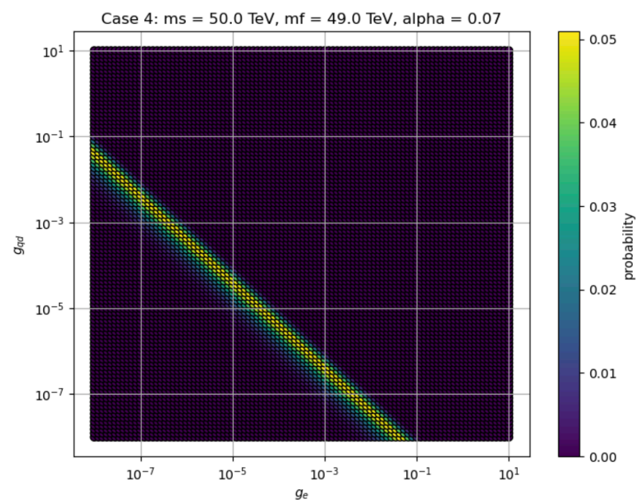

Figure 5

3 Future Plans

As mentioned earlier, the next steps in this project involve utilizing the ManeParse Mathematica package to reproduce the exclusion plot from Ref. [2] using the complete expression for the number of events, equation 2. Once we gain a clear understanding of how the package works and successfully recreate their exclusion plot, we will apply it to our target values of mass and coupling. We anticipate that the other variables in equation 2, such as the cross section and branching ratio, may have a greater influence on the number of events than the probability. If, when we complete the full calculation for N_{obs}, the low coupling regions for TeV scale masses meet the criteria established in Ref. [2], it would provide a strong indication that these LLPs could be detected exhibiting LNV physics in MATHULSA. With this, we hope that this detector will be built in the near future, and we can validate our theoretical calculations with concrete experimental evidence.

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We corroborated our results with simulations in MadGraph5_aMC@NLO [13] to ensure the validity of our work. MadGraph is a computer program that can be used to simulate the decay of different types of particles. We uploaded the particles and parameters of the O2 Model and ran many simulations for different masses and coupling strengths. To learn more, visit https://launchpad.net/mg5amcnlo or reference [13].

We thank Gang Li and the authors of the paper "Lepton Number Violation: from $0\nu\beta\beta$ Decay to Long-Lived Particle Searches" [2] for allowing us to access the Mathematica notebook and ManeParse package, so that we could further our research, and all the additional resources shared to help further my understanding.

References

[1] Tao Peng, Michael J. Ramsey-Musolf, and Peter Winslow. "TeV lepton number violation: From neutrinoless double-β decay to the LHC". In: Phys. Rev. D 93.9 (2016), p. 093002. DOI: 10.1103/PhysRevD.93.093002. arXiv: 1508.04444 [hep-ph].

[2] Gang Li et al. "Lepton number violation: From $0\nu\beta\beta$ decay to long-lived particle searches". In: Phys. Rev. D 105.11 (2022), p. 115018. DOI: 10.1103/PhysRevD.105.115018. arXiv: 2109.08172 [hep-ph].

[3] D.B. Clark, E. Godat, and F.I. Olness. "ManeParse : A Mathematica reader for Parton Distribution Functions". In: Computer Physics Communications 216 (July 2017), pp. 126–137. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2017.03.004. URL: http://dx.doi.org/10.1016/j.cpc.2017.03.004.

[4] A. D. Sakharov. "Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe". In: Pisma Zh. Eksp. Teor. Fiz. 5 (1967), pp. 32–35. DOI: 10.1070/PU1991v034n05ABEH002497

[5] Yuan-Zhen Li, Michael J. Ramsey-Musolf, and Jiang-Hao Yu. "Does the Electron EDM Preclude Electroweak Baryogenesis ?" In: (Apr. 2024). arXiv: 2404.19197 [hep-ph].

[6] Rabindra N. Mohapatra and Goran Senjanovi ć. "Neutrino Mass and Spontaneous Parity Nonconservation". In: Phys. Rev. Lett. 44 (14 Apr. 1980), pp. 912–915. DOI: 10.1103/PhysRevLett.44.912. URL: https://link.aps.org/doi/10.1103/PhysRevLett.44.912.

[7] M. Fukugita and T. Yanagida. "Barygenesis without grand unification". In: Physics Letters B 174.1 (1986), pp. 45–47. ISSN: 0370-2693. DOI: https://doi.org/10.1016/0370-2693(86)91126-3. URL: https://www.sciencedirect.com/science/article/pii/0370269386911263.

[8] Julia Harz et al. "TeV-scale lepton number violation: Connecting leptogenesis, neutrinoless double beta decay, and colliders". In: Phys. Rev. D 110.3 (2024), p. 035024. DOI: 10.1103/PhysRevD.110.035024. arXiv: 2106.10838 [hep-ph].

[9] Henry Lubatti et al. MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LH 2019. arXiv: 1901.04040 [hep-ex]. URL: https://arxiv.org/abs/1901.04040.

[10] Tao Peng, Michael J. Ramsey-Musolf, and Peter Winslow. "TeV lepton number violation: From neutrinoless double-<mml:math xmlns:mml="http://www.w3.org/1998/Math/MathML" display="inline"><mml:mi> </mml:mi></mml:math>decay to the LHC". In: Physical Review D 93.9 (May 2016). ISSN: 2470-0029. DOI: 10.1103/physrevd.93.093002. URL: http://dx.doi.org/10.1103/PhysRevD.93.093002.

[11] Chaochen Yuan et al. "Producing and detecting long-lived particles at different experiments at the LHC". In: Journal of High Energy Physics 2022.2 (Feb. 2022). ISSN: 1029-8479. DOI: 10.1007/jhep02(2022)069. URL: http://dx.doi.org/10.1007/JHEP02(2022)069.

[12] Thomas Junk. "Confidence level computation for combining searches with small statistics". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Det 434.2–3 (Sept. 1999), pp. 435–443. ISSN: 0168-9002. DOI: 10.1016/s0168-9002(99)00498-2. URL: http://dx.doi.org/10.1016/S0168-9002(99)00498-2.

[13] J. Alwall et al. "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations". In: Journal of High Energy Physics 2014.7 (July 2014). ISSN: 1029-8479. DOI: 10.1007/jhep07(2014)079. URL: http://dx.doi.org/10.1007/JHEP07(2014)079.