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

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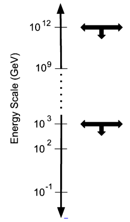
1. Introduction

- In order to explain why our universe is dominated by matter (baryons), with only trace amounts of antimatter (anti-baryons), we need a way to generate such an asymmetry out of the symmetric early universe. The physics of the Standard Model (SM) cannot generate sufficient asymmetry, indicating that the SM is incomplete.
- **Leptogenesis** goes beyond the SM and uses lepton number violating (LNV) physics to generate the baryon asymmetry. In the early universe, LNV decay of heavy right handed Majorana neutrinos (ν_M) could have generated an overdensity in leptons over anti-leptons which was then converted into the observed overdensity of baryons.
- The LNV described above is the mechanism for **standard leptogenesis**, but there are obstacles (**Section 2**) that make it difficult to detect. We focus instead on exploring LNV at the **TeV energy scale**, where certain couplings strengths are compatible with leptogenesis. These weak couplings could result in particles being long lived.
- We use a simplified model (**Section 3**) to simulate the decay of **long lived particles (LLPs)**, and explore which parameter combinations result in the largest predicted number of detection events, N_{obs}^{MATH} , at the proposed detector **MATHUSLA** (**Section 5**).
- Ideally, the regions with the highest N_{obs}^{MATH} would align with those that are viable for being a mechanism for leptogenesis. This would indicate that we could probe leptogenesis viable LNV with MATHUSLA.

2. Exploring LLP Parameter Regions



Standard Thermal Leptogenesis

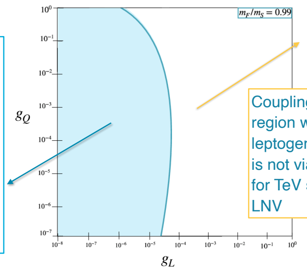
- LNV at this scale - RH neutrino decay - is a viable mechanism for leptogenesis
- Very high energy scale → difficult to detect

TeV scale

- Addtional LNV process at this scale could washout asymmetry, depending on coupling strength

Coupling strengths in the blue region give interactions that could produce observed asymmetry through leptogenesis.

Weak couplings could produce LLPs which decay further from interaction vertex.



Coupling region where leptogenesis is not viable for TeV scale LNV

4. Determining Parameter Regions With High Probability of Detection

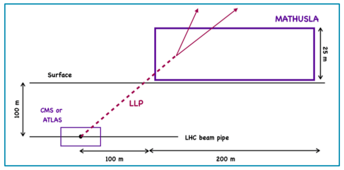
- N_{obs}^{MATH} is a calculation of the predicted number of observed events at the MATHUSL A detector. An event is the detection of a product (either $e^{\pm}$ or jj) of the process shown in **Figure 1**.

$$N_{obs}^{MATH} = \underbrace{\mathscr{L}\ \epsilon_{LLP}^{MATH}\ \epsilon_{geometric}}_{\text{Detector specific - fixed values}}\ \underbrace{P_{decay}\ \sigma_{eF}\ Br_{ejj}}_{\text{Theory based - Varies with } m_S, m_F, g_L, g_Q}$$

$$P_{decay} = e^{-\boxed{L_1}/d} - e^{-\boxed{L_2}/d} \rightarrow d \propto 1/\Gamma_{tot} \xrightarrow[\text{for } m_F \lesssim m_S]{\text{Simplified Model}} \Gamma_{tot} = \frac{3\ m_F^5\ g_L^2\ g_Q^2}{2048\pi^3\ m_S^4} \rightarrow d = \frac{1}{1+\Delta_{QCD}} \frac{1024\pi^3\hbar c}{3} \frac{m_s^5}{m_F^6} (\frac{1}{g_l g_q})^2$$

- Using the simplifications shown above, P_{decay} becomes a four parameter function that can be calculated in Python.
- The calculation of the interaction cross section, σ_{eF}, requires Mathematica package ManeParse [2] to handle parton distribution functions (PDFs).
- To understand how the likelihood of detection varies with coupling strength, we set a fixed mass ratio, and plotted N_{obs}^{MATH} as a function of g_L , g_Q over a grid of values $[10^{-7}, 10^{1}]$. The results are shown in **Figure 3**.

5. MATHUSLA Detector



- The proposed MATHUSLA detector would be built in the vicinity of the Large Hadron Collider (LHC). Its distance from the main interaction point makes it particularly useful for the detection of LLP, the decay products of which would appear further from the interaction point than detectable by CMS or ATLAS.
- The equation for P_{decay} used in **Section 4** is specific to the MATHUSLA detector. $L_1 = 200$ meters, and $L_2 = 230$ meters are the approximate distances to detector from the interaction point in CMS or ATLAS.

3. Using a Simplified Model

- We used a simplified model that introduces three new particles to the SM, with their respective properties shown in Table 1.

	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

- This simplification allowed us to make concrete calculations, in particular we wanted to predict whether a LLP with a certain mass ratio and coupling strength could be detected by the MATHUSLA.
- Our calculations focused on determining the likelihood of detecting the decay products of the process shown in Figure 1.

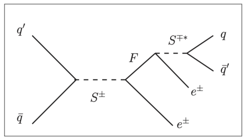


Figure 1. A $pp \rightarrow e^{\pm}e^{\pm}jj$ process in the LHC produces F and an electron/positron. F then decays into an elecron/positron and two quark jets.

- We simulate the decay of F in this process, varying the coupling strengths g_l and g_q, for a fixed mass ratio m_F/m_S.
- To maximize the discovery potential, we focused on the regime $m_S > m_F$; meaning, we first produced S and then we have the cascade decays.

6. Results & Conclusions

- **Figure 3** shows a contour plot for N_{obs}^{MATH}, with yellow indicating the highest predicted number of events, and the deep purple indicating the lowest (near or equal to zero).

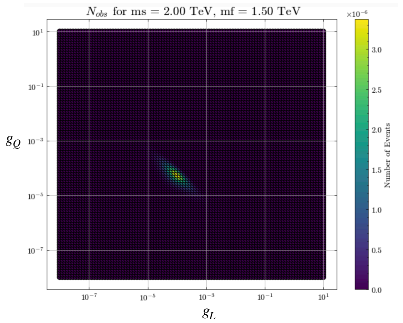


Figure 3

- The colorbar indicates that for this particular mass ratio, the predicted number of decay events observed at MATHUSLA is on the order of 10^{-6}, which is essentially neglible.
- We replicated this plot for various mass ratios on the TeV scale, and found that even if N_{obs}^{MATH} increased, it was only at stronger coupling strengths that are not be compatible with long lived particles.
- We conclude that this method - searching for decay products at MATHUSLA far from the LHC interaction point - has a very low probability of detecting LLPS in the parameter region for which they could be a viable mechanism for leptogenesis.

7. Recommendations

- Our conclusion (**section 6**) does not preclude LLPs from being a viable mechanism for leptogenesis, but means that other methods or detectors would need to be utilized to probe this region of LNV.
- There are other methods available to search for LLPs in the LHC or other colliders such as: dissapearing tracks, delayed calorimeter signals, displaced hadronic jet in the calorimeter or in the inner detector, or searching for a displaced electron pair.
- Without further investigation into how to detect LLP of the coupling strengths and mass scales, it is unlikely we will be able to detect LLP at MATHUSLA in the regions required for leptogenesis.

Acknowledgements & References

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