**Report of CERN Summer Student Programme 2024**

# Feasibility study of observation of inverse neutrinoless double beta decay at the LHC


Dang Bao Nhi NGUYEN

Supervisors: Dr. Tomas SYKORA, Dr. Christoph REMBSER

CERN, Geneva, Switzerland, 2024


## 1 The problem

In this project, we focus on studying the possibility of observation of the neutrinoless double beta decay, a process associated with the Majorana neutrino

$$p + p \to n + n + e^+ + e^+. \tag{1}$$

Specifically, we investigate this process in case neutrons are detected by the Zero Degree Calorimeter (ZDC) detector on both sides of Interaction Point 1 (ATLAS).

## 2 Model and process amplitude

We study the process using the effective Lagrangian

$$\mathcal{L}_{\text{int}} = \left( \frac{g}{2\sqrt{2}} \overline{p} \gamma^\mu (c_V - c_A) n W^+_\mu + \text{h.c.} \right) + \left( \sum_{i=1}^{3} U_{ie} \frac{g}{2\sqrt{2}} \overline{\nu}_{\text{M}} \gamma^\mu (1 - \gamma^5) e W^+_\mu + \text{h.c.} \right) \tag{2}$$

where $g$ is the coupling constant of the weak interaction, $c_V$ and $c_A$ are vertor current and axial current couplings, $U_{ie}$ is the Pontecorvo-Maki-Nakagawa-Sakata matrix, $p, n, W, e$ are fields describing proton, neutron, $W$ boson, electron respectively, and $\nu_{\text{M}}$ is the Majorana neutrino field.

There are 4 diagrams, one of them shown in Figure 1, describing above process and the full amplitude is written as

$$\mathcal{A} = \mathcal{A}_1 - \mathcal{A}_2 - \mathcal{A}_3 + \mathcal{A}_4 \tag{3}$$

in which

$$\mathcal{A}_2 = \mathcal{A}_1(p_1 \leftrightarrow p_4), \qquad \mathcal{A}_3 = \mathcal{A}_1(p_2 \leftrightarrow p_3), \qquad \mathcal{A}_4 = \mathcal{A}_1(p_1 \leftrightarrow p_4, p_2 \leftrightarrow p_3), \tag{4}$$

where $\mathcal{A}_1$ is the amplitude corresponding to the diagram in Figure 1. The minus signs in front of $\mathcal{A}_2$ and $\mathcal{A}_3$ terms in equation (3) are due to the interchange of one pair of fermions.

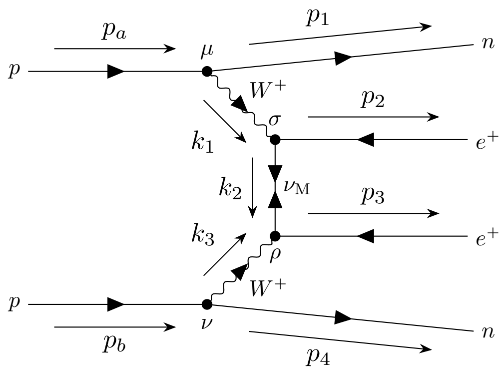


Figure 1: One of the possible Feynman diagram for inverse double beta decay corresponding to amplitude $\mathcal{A}_1$, see the text.

# 3 Analytical and numerical results

## 3.1 Analytical results

From the amplitude $\mathcal{A}$, we obtain the explicit form of the process probability.

The expression is too complicated to be presented here. The full expression and detail calculations can be found in the full report [1].

## 3.2 Numerical results

Using MadGraph 5 [2], we obtain the cross section for the process and for the background as

$$\sigma_{\text{signal}} = 5.715 \times 10^{-1} \pm 2.6 \times 10^{-3}\,\text{pb}, \qquad (m_N = 1.5\,\text{TeV}), \tag{5}$$

$$\sigma_{\text{background}} = 1.684 \times 10^{4} \pm 6.7 \times 10^{1}\,\text{pb}. \tag{6}$$

After the cuts which are explained in [1], the current ratio of cross sections of the signal ($m_N = 1.5\,\text{TeV}$) to the cross section of the background is

$$\frac{\sigma_{\text{signal}}}{\sigma_{\text{background}}} \approx 1.41. \tag{7}$$

We are still working to improving the cut to increase the ratio of signal to background.

# 4 Conclusion

Using the effective Lagrangian, we have obtain the expression of the process probability and the numerical result of the process cross section. The huge background can be significant reduced to distinguish the signal.

Detailed results and comments are given found in the full report [1].

# 5 Project experience and Key learnings

## Project Activities

I started the project by considering the process and determining the Lagrangian that could describe the process. The project progressed through the following key steps:

1. State the process and determine the Lagrangian.
2. Draw Feynman diagrams and write correspoding amplitude expression.

3. Calculate the process probability.
4. Calculate the process and background cross section by Madgraph 5.
5. Estimate the limits of scattering angles and pseudo rapidity of the final particles so that the neutrons can be detected by the ZDC.
6. Reduce the process background by introducing appropriate cuts.
7. Build the phase space for Monte Carlo integration on the cross section over a partial phase space (in progress)

### Key learnings

As a result of these activities, I have gained the following knowledge and skills:

- seesaw mechanism which explained the mass of neutrinos [3].
- basic concept, mechanism and Feynman rules of Majorana neutrino [3, 4].
- technique of Monte Carlo integration, especially the Monte Carlo integration over the phase space of a scattering process [5].
- helicity amplitude method used for numerical calculating the process amplitude and squared amplitude at tree level [6, 7].
- mastered the use of tools:
  - FeynRules [8], used for building models for MadGraph, based on the appropriate Lagrangian.
  - TRACER [9], used for calculating the trace of Dirac gamma matrices.
  - MadGraph 5 [2], used to generate events and calculate process cross section.
  - MadAnalysis 5 [10], used to calculate and plot graphs for events generated by MadGraph 5.
- technique of reducing process background by cuts based on the different topology between the signal and the background.

## 6 Acknowledgements

I would like to express my deepest gratitude to my supervisors, Dr. Tomas Sykora, Dr. Christoph Rembser, and CERN, for the incredible opportunity to work under their guidance at CERN. Your support and guidance have taught me so much and have been essential to my personal and professional development. I truly appreciate everything you have done.

A special thanks to Logan S. Switzer, Chloe Hooper, and Naisir – my CERN summer colleagues – may we all continue to chase and achieve our dreams. I thank to everyone who took the time to explain things and contribute to my work, your insights have been truly instrumental. Thank you all for making this journey both rewarding and unforgettable.

## References

[1] https://cds.cern.ch/record/2916689

[2] J. Alwall *et al*, *Journal of High Energy Physics* **2014**, 2014.

[3] W. Rodejohann, *Phys. Rev. D* **81**, p. 114001, 2010.

[4] J. Gluza and M. Zraek, *Phys. Rev. D*, **45**, pp. 1693–1700, 1992.

[5] E. Byckling and K. Kajantie, *Particle Kinematics (chapters I-VI,X)*, Finland: University of Jyvaskyla , 1971.

[6] K. Mawatari and Y. Kakaesu, *Eur. Phys. J. C 71*, p. 1640, 2011;

[7] P. de Aquino *et al*, *Comput. Phys. Commun.* **183**, pp. 2254-2263, 2012.

[8] A. Alloul *et al*, *Comput. Phys. Commun.* **185**, pp. 2250-2300, 2014.

[9] M. Jamin and M. E. Lautenbacher, *Comput. Phys. Commun.* **74**, pp. 265–288, 1993.

[10] E. Conte, B. Fuks, and G. Serret, *Comput. Phys. Commun.* **184**, pp. 222-256, 2013.