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

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Abstract

The nature of the neutrino is one of the most fundamental questions in modern neutrino physics: is it a Dirac or Majorana particle? In this project, we focus on studying the possibility of observation of the neutrinoless double beta decay, a process associated with the Majorana neutrino. Specifically, we will investigate this decay process where the neutrons are detected by the Zero Degree Calorimeter (ZDC) detector on both sides of Interaction Point 1 (ATLAS).

Neutrinos: Dirac or Majorana type?

Dirac fermion

It's well known that a Dirac neutrino ν^{D} can only be massive if it possesses both left-handed (L) and right-handed (R) components

$$\mathcal{L}^{\text{Dirac}}_{\text{free}} = \bar{\nu}^{\mathrm{D}}_{\mathrm{L}} i\partial\!\!\!/ \nu^{\mathrm{D}}_{\mathrm{L}} + \bar{\nu}^{\mathrm{D}}_{\mathrm{R}} i\partial\!\!\!/ \nu^{\mathrm{D}}_{\mathrm{R}} - m_{\mathrm{D}} \left(\bar{\nu}^{\mathrm{D}}_{\mathrm{R}} \nu^{\mathrm{D}}_{\mathrm{L}} + \bar{\nu}^{\mathrm{D}}_{\mathrm{L}} \nu^{\mathrm{D}}_{\mathrm{R}}\right).$$

Majorana fermion

If charged conjugation of left-handed fermion is a right-handed fermion $\psi^c_{\mathrm{L}} = \psi_{\mathrm{R}}$, then the Majorana fermion defined as

$$\psi^{\mathrm{M}} \equiv \psi_{\mathrm{L}} + \psi^c_{\mathrm{L}}$$

is also identical to its antiparticle $(\psi^{\mathrm{M}})^c = \psi^{\mathrm{M}}$.
Majorana neutrino ν^{M} can be massive without the presence of right-handed component:

$$\mathcal{L}^{\text{Majorana}}_{\text{free}} = \bar{\nu}^{\mathrm{M}}_{\mathrm{L}} i\partial\!\!\!/ \nu^{\mathrm{M}}_{\mathrm{L}} + (\bar{\nu}^{\mathrm{M}}_{\mathrm{L}})^c i\partial\!\!\!/ (\nu^{\mathrm{M}}_{\mathrm{L}})^c - m_{\mathrm{M}} \left((\bar{\nu}^{\mathrm{M}}_{\mathrm{L}})^c \nu^{\mathrm{M}}_{\mathrm{L}} + \bar{\nu}^{\mathrm{M}}_{\mathrm{L}} (\nu^{\mathrm{M}}_{\mathrm{L}})^c\right),$$

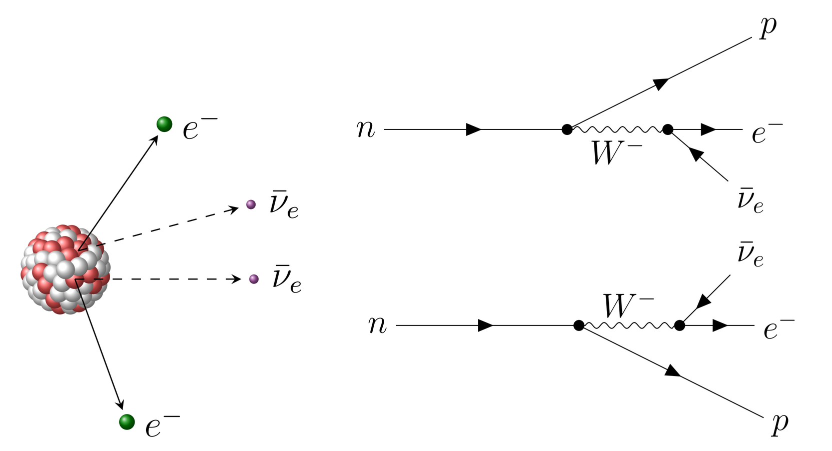
where $\bar{\nu}^{\mathrm{M}}_{\mathrm{L}} = (\nu^{\mathrm{M}}_{\mathrm{L}})^T \mathcal{C}$ and $\mathcal{C}$ is the charge conjugation operator.

Plausibility of Majorana neutrinos

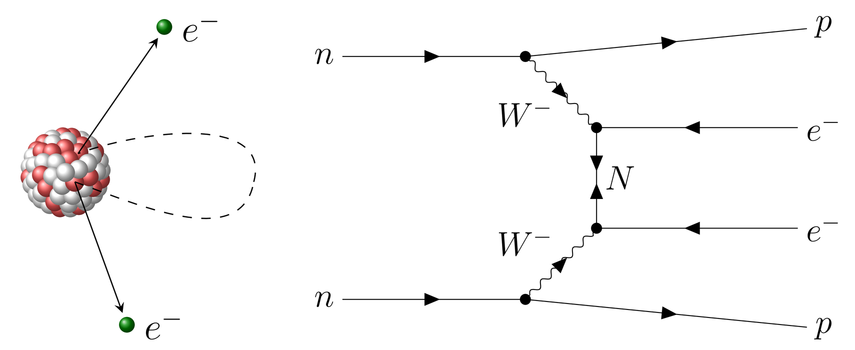
There is a general believe that neutrino are Majorana particles as:

- no right-handed neutrino has been observed so far,
- neutrinos have to have non-zero masses.

Dirac neutrino: double beta decay



Majorana neutrino: neutrinoless double beta decay



Research objectives

Objective 1: estimate the number of possible detected events, using the current mass limits on Majorana neutrinos and including detector acceptance.
Objective 2: consider the background processes and identify opportunities to detect the Majorana neutrino.
Objective 3: if cross section look reasonable and background can be suppressed, then check on existing data for promising signal.

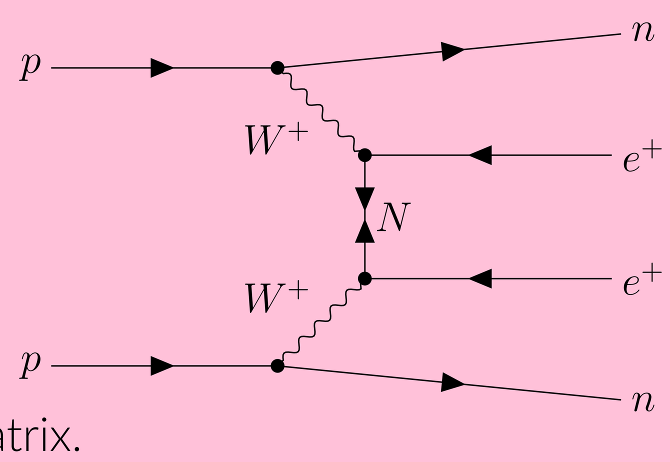
Inverse neutrinoless double beta decay at the LHC

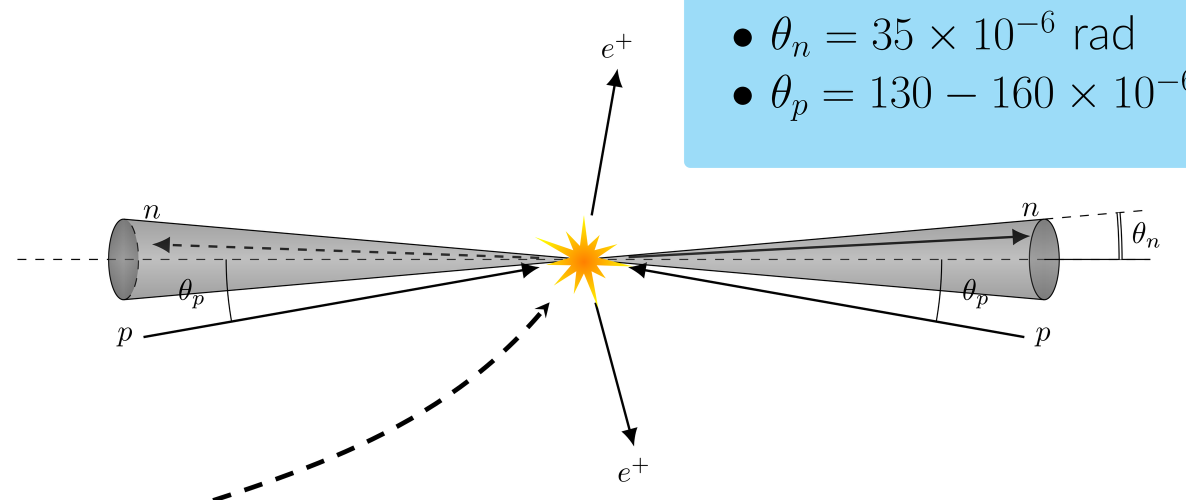
We consider the inverse $0\nu\beta\beta$ decay:

- both neutrons are registered by the ZDC
- most of energy of protons go to neutrons

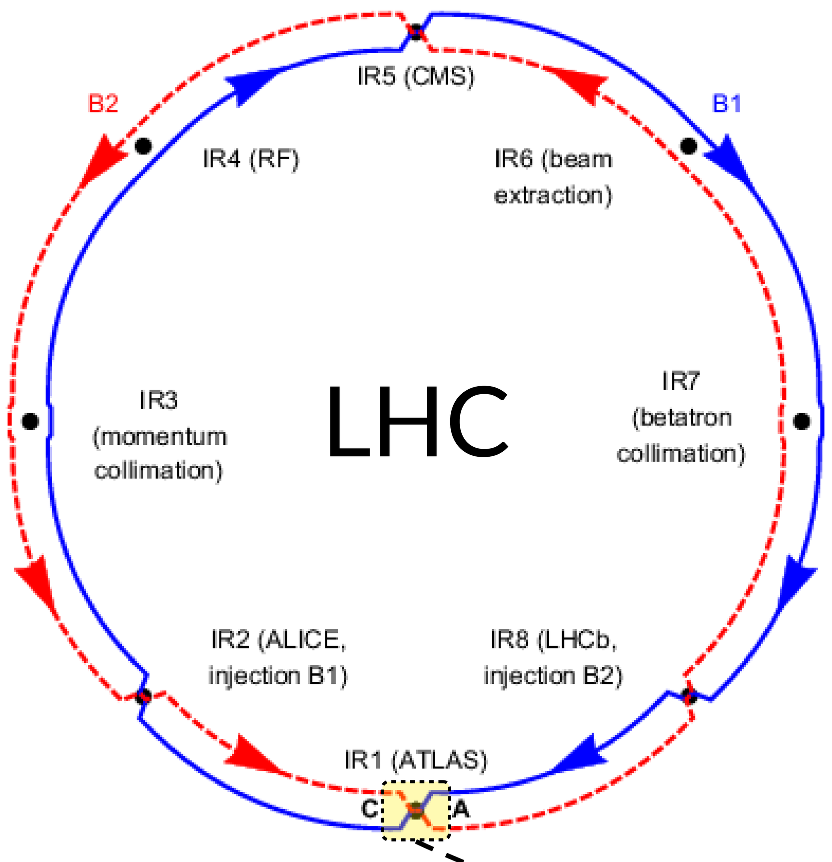
$$\mathcal{L}_{\text{int}} = \frac{g_{\mathrm{W}}}{2\sqrt{2}} \bar{p} \gamma^\mu (c_{\mathrm{V}} - c_{\mathrm{A}}\gamma^5) n W^+_\mu + \text{h.c.} + \sum_{i=1}^{3} U_{ie} \frac{g}{2\sqrt{2}} \bar{\nu}_{\mathrm{M}} \gamma^\mu (1-\gamma^5) e W^+_\mu + \text{h.c.}$$

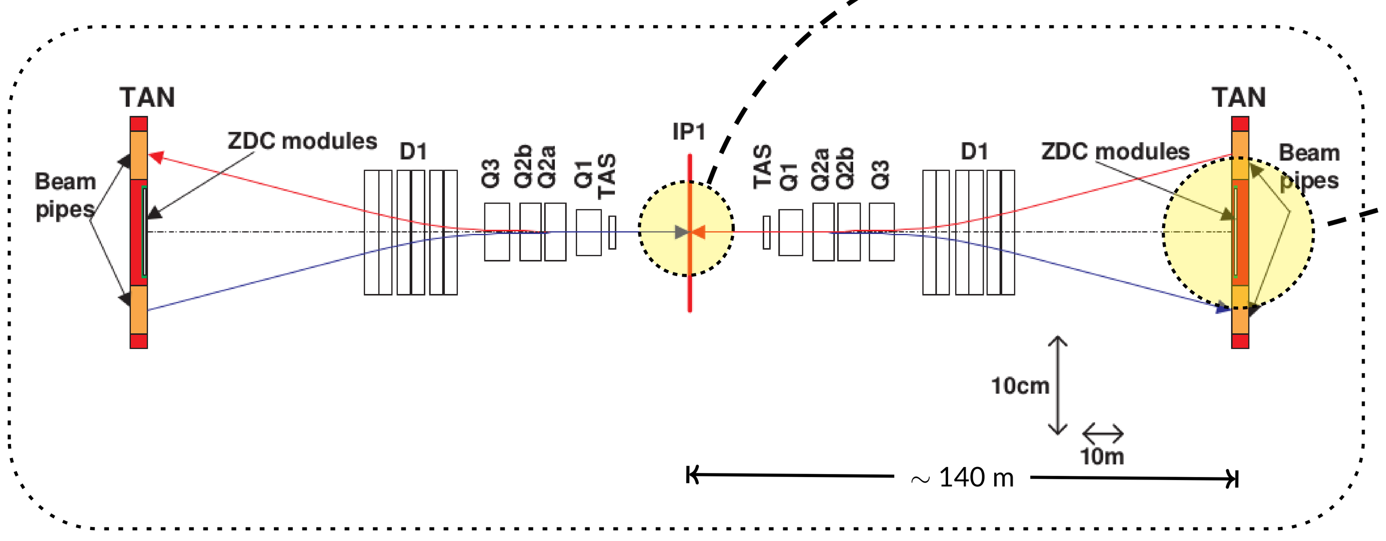
where U is Pontecorvo–Maki–Nakagawa–Sakata matrix.



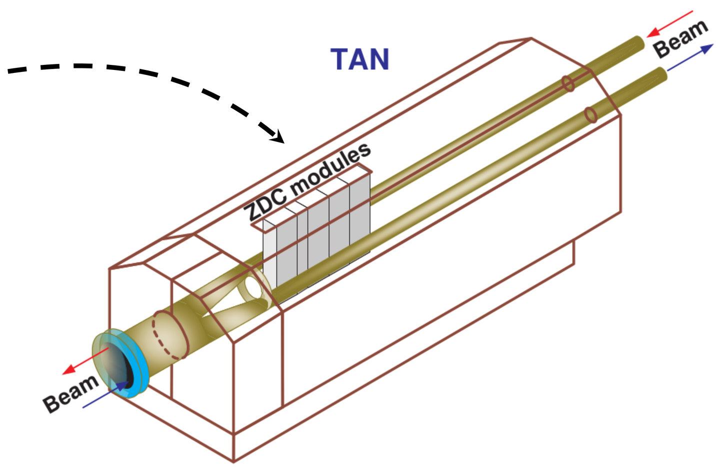


- $\theta_n = 35 \times 10^{-6}$ rad
- $\theta_p = 130 - 160 \times 10^{-6}$ rad





TAN - Target Absorber for Neutrals



ZDC - Zero Degree Calorimeter - observes forward going neutral particles at approximately zero degrees to the incident beams on either side of IP1.

First results

Amplitude

$$\mathcal{A}_1 = i\frac{g^4}{32} c_V^2 \times \frac{1}{(p_a - p_1)^2 - m_W^2} \times \frac{1}{(p_b - p_4)^2 - m_W^2} \times \frac{m_N}{(p_a - p_1 - p_2)^2 - m_N^2} \times \left[\bar{u}_1 \gamma^\mu (1 - \epsilon\gamma^5) u_a\right] \times \left[\bar{u}_4 \gamma^\nu (1 - \epsilon\gamma^5) u_b\right] \times \left[\bar{u}_3 \gamma_\nu \gamma_\mu (1 - \gamma^5) v_2\right]$$

$$\mathcal{A} = \mathcal{A}_1 - \mathcal{A}_1(p_1 \leftrightarrow p_4) - \mathcal{A}_1(p_2 \leftrightarrow p_3) + \mathcal{A}_1(p_1 \leftrightarrow p_4, p_2 \leftrightarrow p_3).$$

Numerical result [a]

Light neutrino $m_{\mathrm{M}} = 1.5$ meV:

$$\sigma = 1.405 \times 10^{-14} \pm 5.3 \times 10^{-17} \text{ fb} \longrightarrow \text{too small!}$$

Heavy neutrino $m_{\mathrm{M}} = 1.5$ TeV:

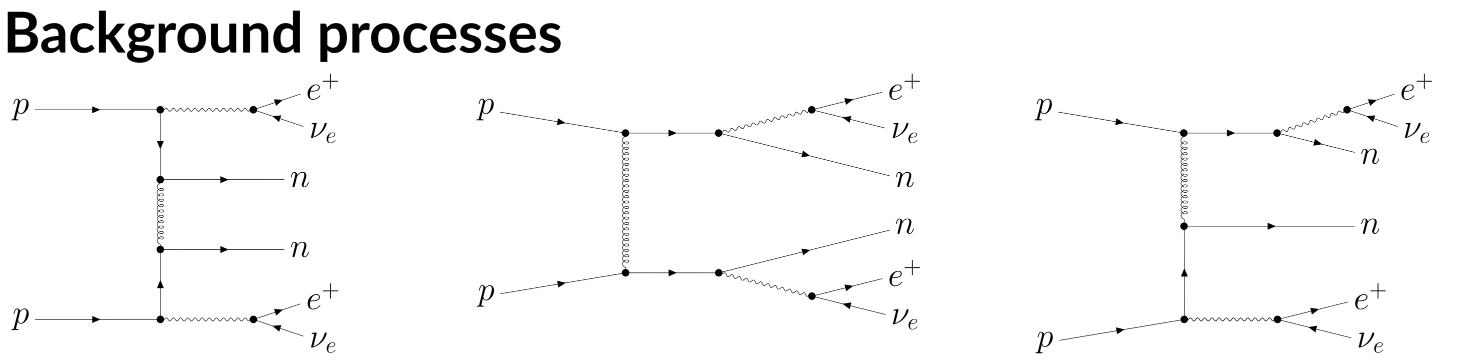
$$\sigma = 571.5 \pm 2.6 \text{ fb}$$

For ATLAS Run 2 (13 TeV, 140 fb^{-1}):

$$N_{\text{events}} = \sigma \times \text{integrated luminosity} \approx 571.5 \text{ fb} \times 140 \text{ fb}^{-1} \approx 80 \times 10^3 \text{ !!}$$

[a] Results are taken by MadGraph5 over the whole phase space, not limited to the acceptance of ZDC.

Background processes



The background ($\mathcal{L}_{\text{SM}}$ used) is huge for light Majorana neutrino but not for heavy Majorana neutrino

$$\sigma = 6.468 \times 10^{-1} \pm 1.6 \times 10^{-3} \text{ fb}$$

Work in progress

We have obtained the initial results of the cross-section of the process. However, the cross-section encompasses the entire phase space rather than being limited to the acceptance range of the detector, also very limited luminosity was taken.

Next steps:

- calculate the cross section and event number, for both signal and background, within the phase space given by the ZDC detector acceptance and taking into account the very limited luminosity taken by the ZDC detector during proton-proton runs. The study can eventually serve as an argument to keep the ZDC detector during proton-proton runs in future.
- check for the measurement data.

References

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