PROCEEDINGS OF SCIENCE

Muon Veto for the LEGEND Experiment

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The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless $\beta\beta$ **D**ecay (LEGEND) is an experiment searching for neutrinoless $\beta\beta$ decay of the ^{76}Ge isotope. LEGEND-1000, with 1000 kg of ^{76}Ge mass, is designed to reach half-life sensitivity of $T_{\frac{1}{2}} > 10^{28}$ years. To be sensitive to such a half life, a number of measures are required to reduce background events. For the current experimental phase, LEGEND-200 utilizes a Water-Cherenkov-Veto system to actively reduce background noise from radioactive isotopes and cosmic radiation, such as muons. It uses photomultiplier tubes (PMTs) as light sensors in a water-tank covered with a reflective foil to enhance the collection of light inside the water volume. This muon veto has been stably taking data since March 2023. Regular calibration of the PMTs ensures measurements of up to 100 photoelectrons per PMT. A first look on the data of the muon veto shows a stable total muon rate of $\approx$ 35 mHz over two months. A small area of the muon veto directly below the cryostat, called the "Pillbox", can increase the detection efficiency of muons in the experiment through determining coincidences between the muon veto and the liquid argon (LAr) instrumentation or High Purity Germanium (HPGe) detectors. It has been demonstrated that 20% of the muon veto PMTs can detect $\approx$ 70.8% of the coincident muon events. Considering these results, plans for the improved LEGEND-1000 muon veto are presented, including an optimised PMT distribution.

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1. Introduction

LEGEND is an experiment using ^{76}Ge to search for the neutrinoless double beta decay. The current experimental phase, LEGEND-200, contains 200 kg of HPGe detectors enriched in ^{76}Ge, surrounded by LAr instrumentation and a muon veto as active background shielding. The experiment will take data for approximately five years to achieve a sensitivity of $T_{\frac{1}{2}} > 10^{27}$ yr and a background rate of 0.5 cts/(FWHM·t·yr). The proposed experimental phase LEGEND-1000 will deploy 1000 kg of enriched HPGe detectors to achieve an even lower background of less than 0.025 cts/(FWHM·t·yr)and sensitive to a half life $T_{\frac{1}{2}} > 1.3 \cdot 10^{28}$ yr [1].

LEGEND-200 uses a water Cherenkov veto system for active background rejection. It uses PMTs as light detectors in a water-tank covered with a reflective foil to increase the light yield inside the water. The muon veto has been reused from the GERDA experiment [2]. Some PMT positions were changed to improve the detection of muons going through the center of the tank and therefore through the HPGe detectors and the LAr instrumentation. Therefore, the PMTs of LEGEND-200 have a higher distribution across the Floor and Pillbox (PB) than across the Wall (cf. figure 1).

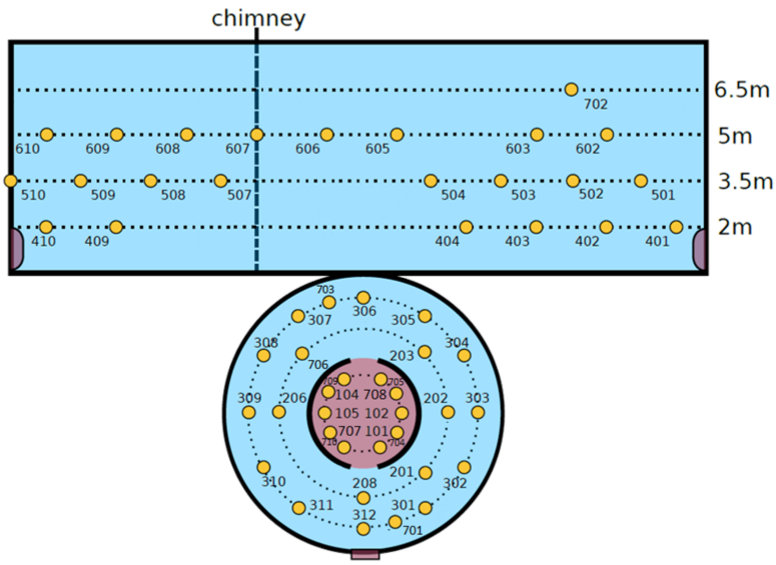

Figure 1: PMT channel map of the muon veto of LEGEND-200. All PMTs except one were placed across the Floor and Pillbox from the top row. Gaps in the middle of the map are due to PMTs broken during the GERDA upgrade to LEGEND-200. The red area in the middle of the Floor is the Pillbox, where now 10 PMTs are mounted. Adapted from [3].

2. Calibration

The muon veto is calibrated using five LED diffuser balls, which are pulsed to measure the single photoelectron (p.e.) peak of the PMTs (cf. figure 2). The calibration goal is a gain which corresponds to 30 ADC channels for 1 p.e. This allows to measure peaks of up to 100 p.e. by a 12-bit ADC and a baseline at 1000 ADC channels. The voltage supplied to the PMTs is changed according to equation (1)

$$V_{target} = V \left(\frac{g_{target}}{g} \right)^{\frac{1}{kn}}, \quad (1)$$

where n=12 Dynodes, g_{target} =30 ADCs, the gain $g = \frac{Q}{e}$, the supplied Voltage V and a constant k.

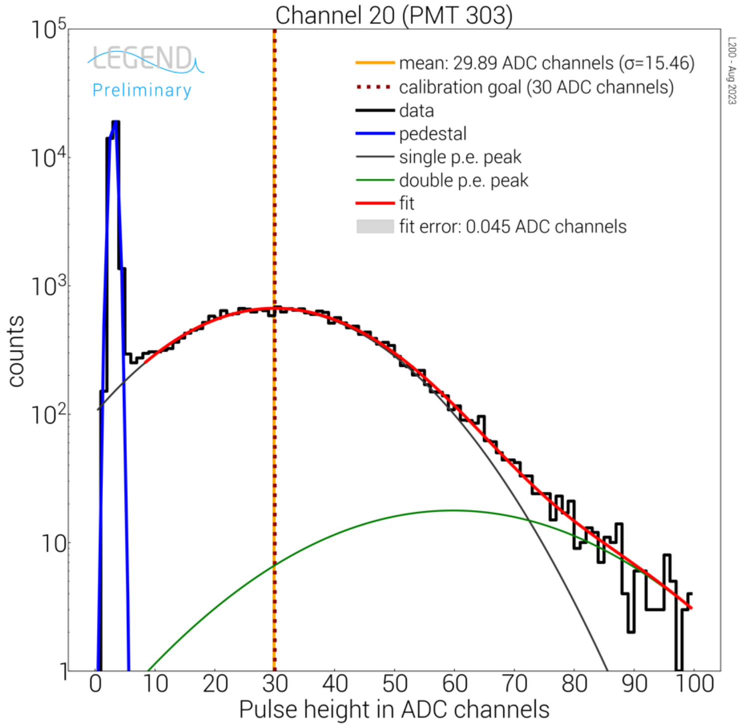

Figure 2: Example of a single p.e. peak fit (red) of a PMT during calibration with a pedestal due to electric noise (darkblue), single p.e. peak (gray) and indicated double p.e. peak (green). The measured mean of the single p.e. peak (orange) lays over the calibration goal (dotted red line).

3. Muon Veto Events

The first measurement campaign after commissioning of LEGEND-200 started on March 12^{th}, 2023 with data taking period p03, followed by period p04 with enabled LAr trigger started on April 15^{th}, 2023 (cf. figure 3 and 4). Muon-induced events are identified in the collected data through the application of two distinct cuts. First, a multiplicity cut is used to remove events caused by scintillation of the reflective foil by requiring a $multiplicity$ >12 and $p.e.$ >30. Second, non-physical data is cut out by requiring $\frac{p.e.}{multiplicity}$ >0.4 to make a conservative cut, since the p.e. trigger of a single PMT is 0.5 p.e. (cf. figure 3). The corresponding muon rates of the PMTs are shown in figure 4 per day of data taking. The peak on the 4^{th} of April 2023 is caused by a broken PMT on the wall, which was flashing while it was breaking. Otherwise, data rates have been stable and lead to a total muon rate of ≈ 35 mHz.

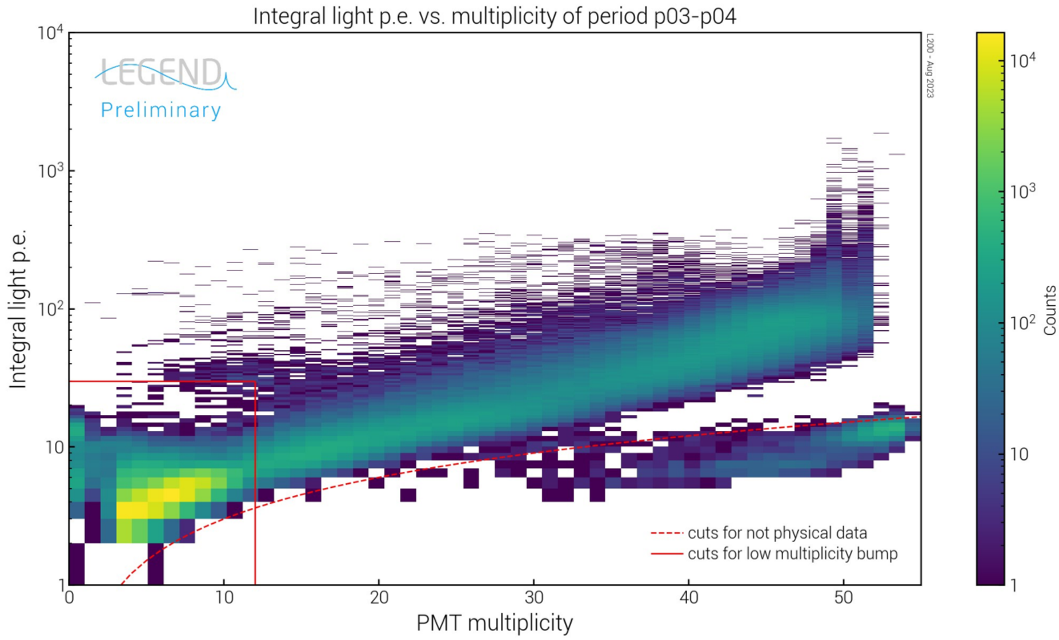

Figure 3: Integral light as a function of multiplicity with cuts. The red box region highlights events caused by scintillation in the reflective foil.

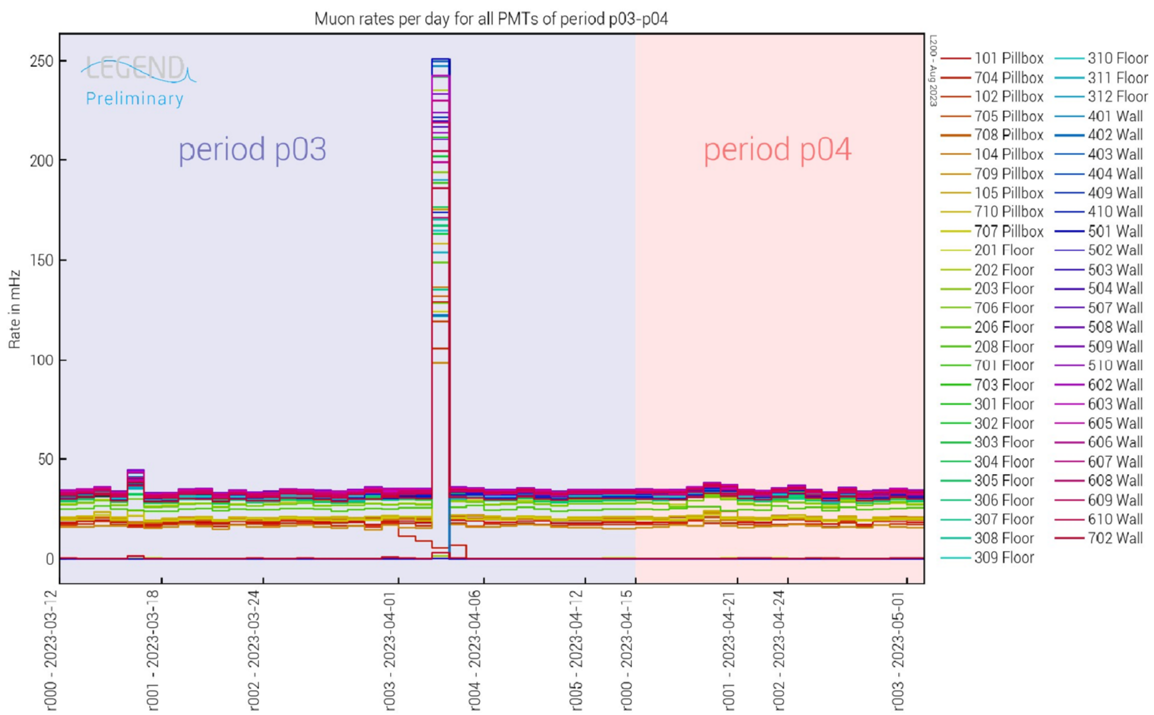

Figure 4: Muon event rate of each PMT as a function of time, where the peak in period p03 is caused by a flashing PMT.

The coincidence rates of muon events in both the LAr/HPGe detector system, and the muon veto were stable during the runs. The detection efficiency in period p04 increased after the LAr insturmentation was enabled as an additional trigger. The PB, approximately 20% of all muon veto PMTs, detects 70.8% of the coincidence muons measured by the muon veto and the LAr/HPGe detector system.

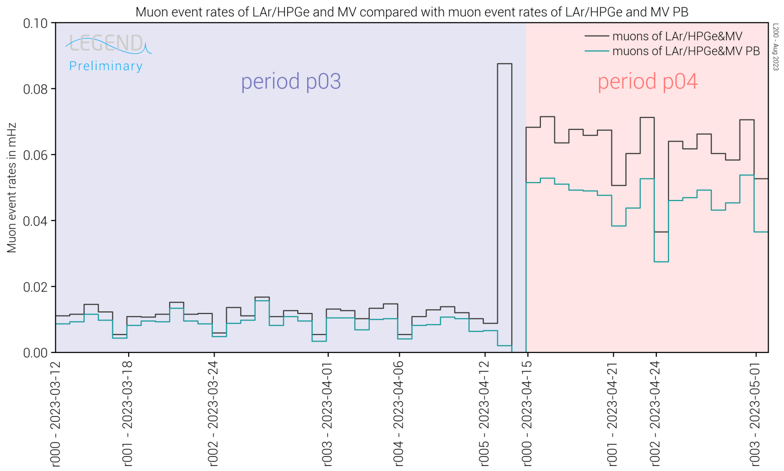

Figure 5: Muon event rates of LAr/HPGe system and Muon Veto (grey) and LAr/HPGe system and Pillbox of the Muon Veto (blue) as function of time.

4. Summary and Outlook

The muon veto of LEGEND-200 has been successfully implemented as an active background shielding. Regular calibrations are taken to ensure measurements of up to 100 p.e. per PMT. A first look at the muon veto data shows that, after two analysis cuts, a stable total muon rate of $\approx$ 35 mHz is measured. In addition, the importance of the Pillbox is shown by the LAr/HPGe instrumentation and the muon veto. Just 20% of the muon veto PMTs detected $\approx$ 70.8% of the coincident muon events. The water Cherenkov veto system of LEGEND-1000 will be built in a larger tank. Compared to LEGEND-200, the muon veto of LEGEND-1000 will have a higher density of PMTs exclusively distributed across the floor and Pillbox, with a different reflective foil to reduce accidental coincidences.

References

[1] N. Abgrall et al. (LEGEND Collab.), LEGEND-1000 Preconceptual Design Report, arXiv:2107.11462, 2021.

[2] M. Knapp et al., The GERDA Muon Veto Cherenkov Detector, https://www.mpi-hd.mpg.de/gerda/public/2008/c08_ndip08_MuonVeto_mk.pdf, 2008.

[3] K. Freund, Muonic Background in the GERDA $0\nu\beta\beta$ Experiment, https://www.mpi-hd.mpg.de/gerda/public/2014/phd2014_kaiFreund.pdf, 2014.