NC STATE UNIVERSITY

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Background Modeling for LEGEND-200

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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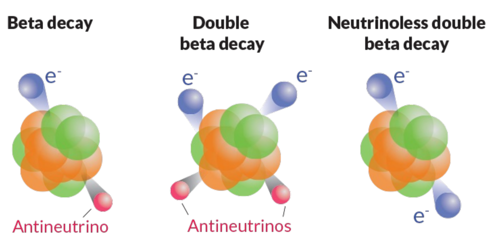
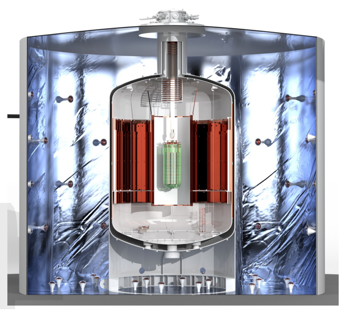
0νββ and LEGEND



0νββ: a hypothetical process, allowed only in ββ decay candidates

Observation of 0νββ confirms ν to be a Majorana particle *i.e.* $\nu = \bar{\nu}$

LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay) is a ^{76}Ge based 0νββ experimental program[1]

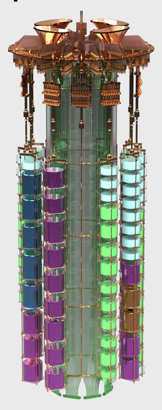


LEGEND-200 : Operational @ LNGS, Italy

LEGEND-1000 : Design and planning phase

LEGEND-200

- ~142kg of enriched ^{76}Ge detectors installed
- ~130kg of detectors working
- Total exposure till date : 10 kg-yr



Comparing with GERDA[2]

- Higher average mass of detectors
- Higher efficiency in detecting background peaks
- Better LAr instrumentation
- Self vetoing capability from WLS materials such as PEN

Brady Bos : LEGEND-200 Data Acquisition, Monitoring and Calibration

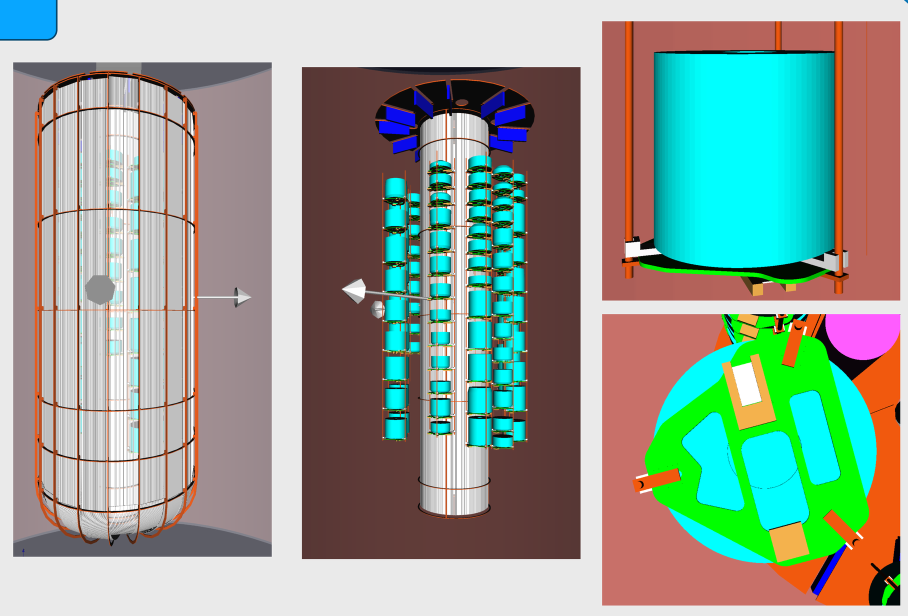
Why model the background?

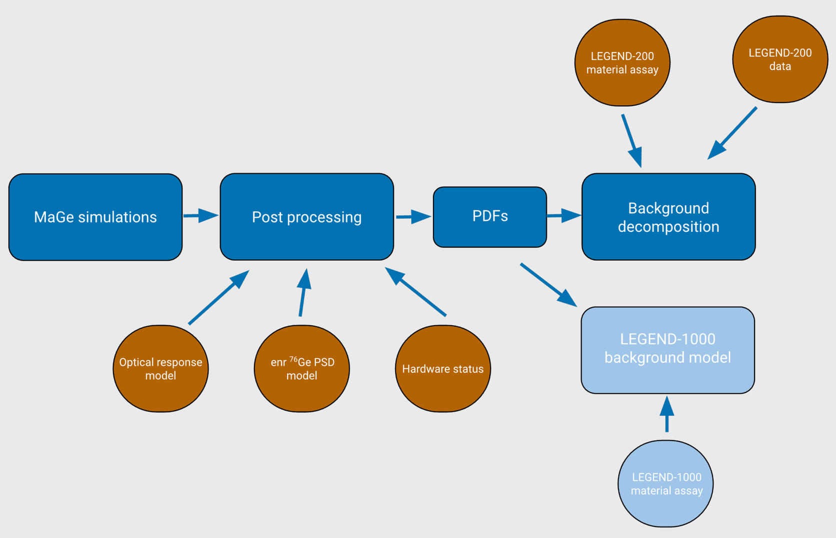
- Background sources for the LEGEND include radioactive decays from the array components, 2νββ in the Ge detectors, gammas and neutrons from the laboratory environment and cosmic ray muons
- Modeling the background contribution is essential as LEGEND operates in almost a background free regime
- A model needed for non-0νββ Beyond Standard Model (BSM) studies
- Background decomposition from the LEGEND-200 experiment would help us compute and make predictions for LEGEND-1000

Samuel Watkins : Searching for Beyond Standard Model Physics with LEGEND-1000

Simulations workflow

- A complex workflow developed to be used with both LEGEND-200 and LEGEND-1000
- Construction of geometry is done using an in-house developed GEANT4 based application MaGe
- Simulations and analysis is done using the resources available at NERSC computing cluster[5]



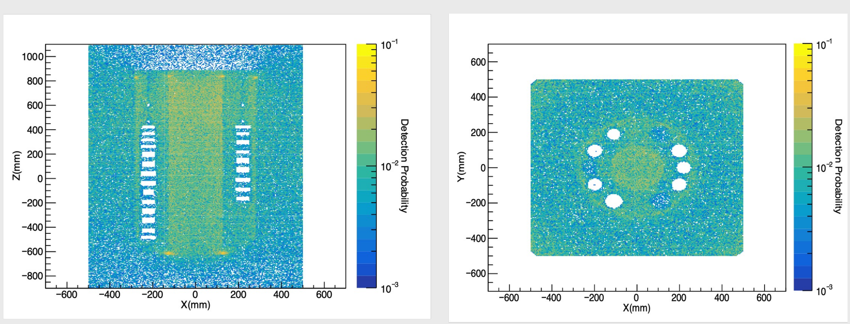


A simplified workflow of simulation package used for background modeling

- Results of the MaGe output are post-processed to include dead layer effects, detector-wise energy resolution, PSA and Liquid Argon response
- To simplify the complex computational challenge, a tier-based workflow[6] is developed and automated using 'Snakemake'[7]

Optical response

- To model the optical response of LAr instrumentation, separate optical simulations are performed using MaGe
- For each bin photon detection probability in the SiPMs calculated
- Total number of expected photo-electrons from an event determined using



XY and XZ slices of the optical maps showing photon detection probabilities in each bin

$$\langle NPE \rangle = \sum_{i}^{steps} E_i \times P_i(x,y,z) \times Y \times Q.E.$$

Number of photo-electrons from an event; Energy deposited by a radioactive particle; Photon detection probability from the optical map; Light Yield of LAr; Quantum efficiency of SiPM

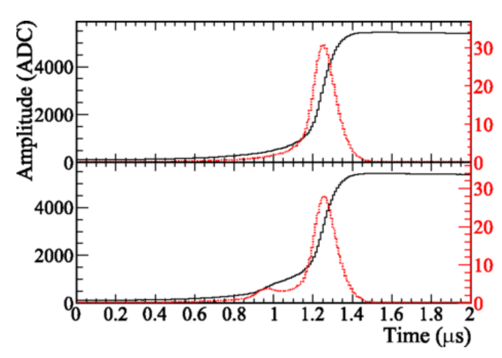
Rosanna Deckert: The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector

Luigi Pertoldi: Liquid argon light collection and veto modeling in GERDA Phase II

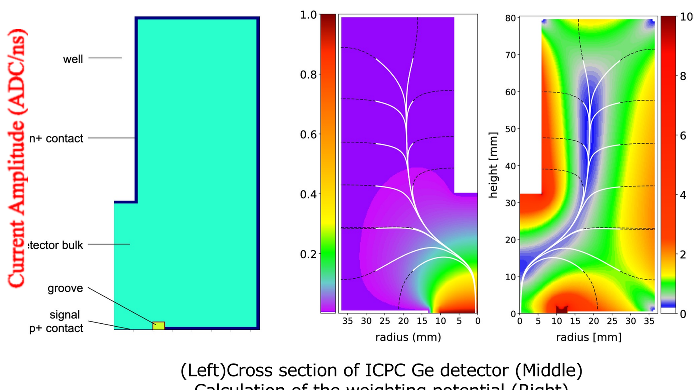
Pulse Shape Analysis

Valentina Biancacci: ^{76}Ge Detectors of LEGEND experiment: Production, Characterization, Performance

- 0νββ is a single-site event (SSE)
- Most LEGEND backgrounds are Multi-site events (MSE)
- Pulse shape analysis (PSA) can distinguish between SSE and MSE
- To model the PSA in the Ge detectors, drift times are calculated for each detector
- A drift time cut off is set to match detector response to identify and reject multi-site events



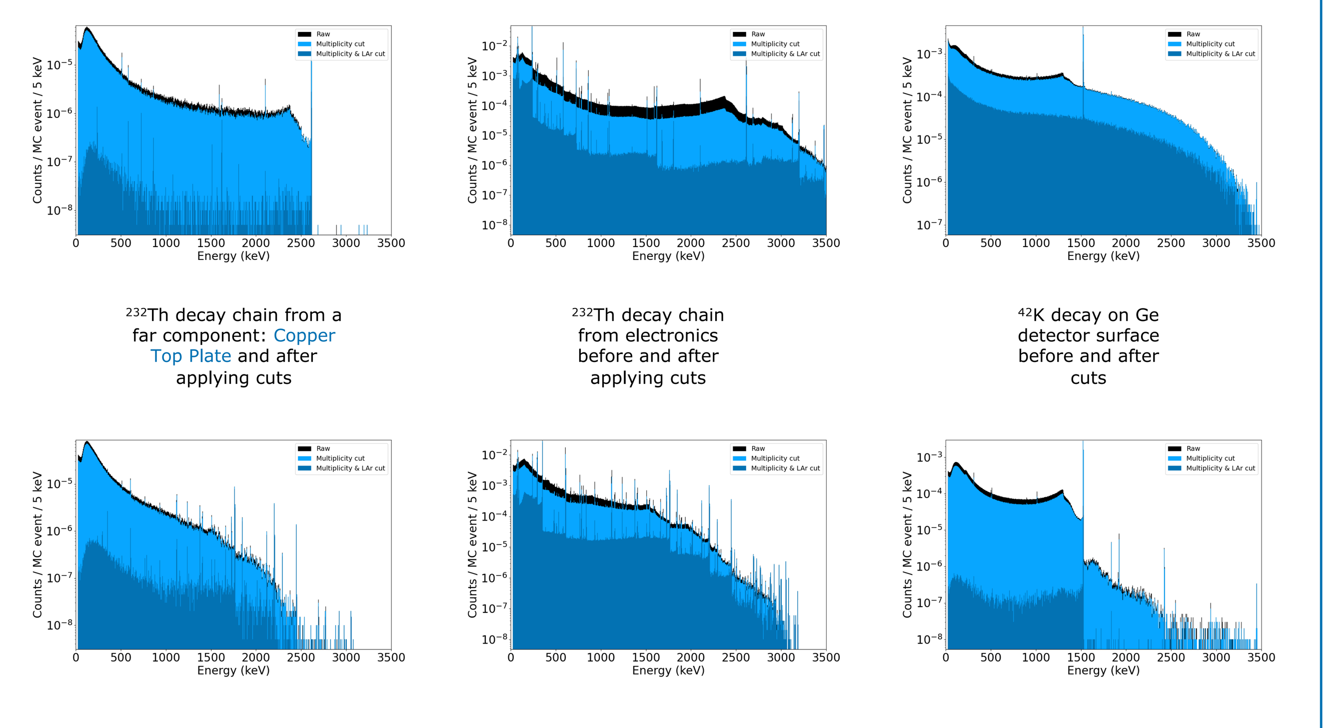
An example pulse shape for single-site (top) and multi-site (bottom) events [8]



(Left)Cross section of ICPC Ge detector (Middle) Calculation of the weighting potential (Right) Electric Field in kV/cm. The black dotted lines are the drift paths of electrons towards n+ contact and the white lines are the drift paths of holes towards the p+ contact

L200 PDFs

- Simulated all expected backgrounds for LEGEND-200
- More than 99% ^{232}Th and 75% ^{238}U chain rejected by multiplicity + LAr cut in ROI ~ 2039keV
- Contribution from the near components is higher than the far components before cuts
- PSA would further suppress ^{232}U, ^{238}Th chain backgrounds
- Nylon shrouds : covering the strings, help suppress the β's from ^{42}K decay



^{232}Th decay chain from a far component: Copper Top Plate and after applying cuts

^{232}Th decay chain from electronics before and after applying cuts

^{42}K decay on Ge detector surface before and after cuts

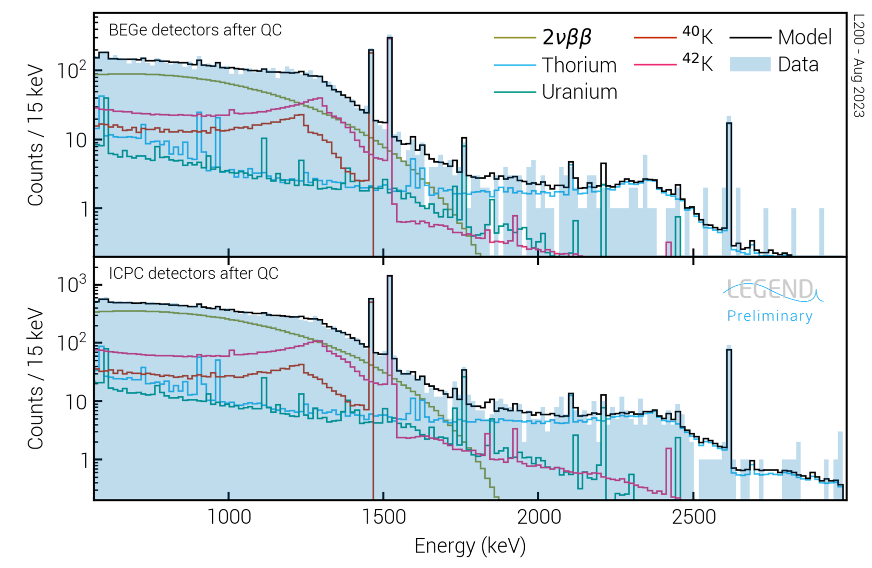
^{238}U decay chain from far component: Copper Top Plate before and after applying cuts

^{238}U decay chain from electronics before and after applying cuts

^{42}K decay in nylon shrouds before and after cuts

Background decomposition

- Background decomposition from the simulation result and first set of LEGEND-200 data collected using Bayesian analysis Toolkit[9][10]
- Screening measurements have been conducted on components to assess radio-contamination
- A gaussian distribution with 1σ uncertainty is used as a priors for fitting
- When *90%C.L.* is available, an exponential prior distribution is used with 90% area covering the values from *0-90%C.L.* upper limit
- In case of no measurements available, a uniform prior distribution assigned
- A difference in data and the screening measurements would result in significant difference between the prior and the posterior
- This can provide insights into the background source and be instrumental in the modeling process



A background decomposition of first set of data after applying quality cuts (QC). The model is fitted separately for Broad Energy Germanium (BEGe) and Inverted coaxial point-contact (ICPC) detectors using a mixture of PDFs that includes 30 independent components, grouped by physics process in the spectra above and summed over all source locations in the array

Next Steps

- The fits and the model are preliminary and would be more refined as we collect more data from the experiment
- Perform systematic studies to apply a dead layer model for the Ge detector surfaces as well as a PSA model to reject multi-site events
- String wise and detector-type wise estimation of background rate will give us insight into the nature and the location of the background sources in the array

References

[1] Abgrall, N., et al. The large enriched germanium experiment for neutrinoless double beta decay (LEGEND), AIP Conference Proceedings. Vol. 1894. No. 1. AIP Publishing LLC, 2017.
[2] GERDA Collaboration., Agostini, M., Bakalyarov, A.M. *et al.* Upgrade for Phase II of the Gerda experiment. *Eur. Phys. J. C* **78**, 388 (2018). https://doi.org/10.1140/epjc/s10052-018-5812-2
[3] Abgrall, Nicolas, et al. The Majorana Demonstrator neutrinoless double-beta decay experiment, Advances in High Energy Physics, 2014, (2014).
[4] Abgrall, N., et al. LEGEND-1000 preconceptual design report, arXiv preprint, arXiv:2107.11462 (2021).
[5] https://www.nersc.gov/
[6] https://github.com/legend-exp/legend-simflow.git
[7] Mölder, F., Jablonski, K.P., Letcher, B., Hall, M.B., Tomkins-Tinch, C.H., Sochat, V., Forster, J., Lee, S., Twardziok, S.O., Kanitz, A., Wilm, A., Holtgrewe, M., Rahmann, S., Nahnsen, S., Köster, J., 2021. Sustainable data analysis with Snakemake. F1000Res 10, 33.
[8] Alvis, S.I., et al. Multisite event discrimination for the majorana demonstrator, Phys. Rev. C, 99.065501 (2019)
[9] https://github.com/bat/bat.git
[10] https://github.com/gipert/hmixfit.git