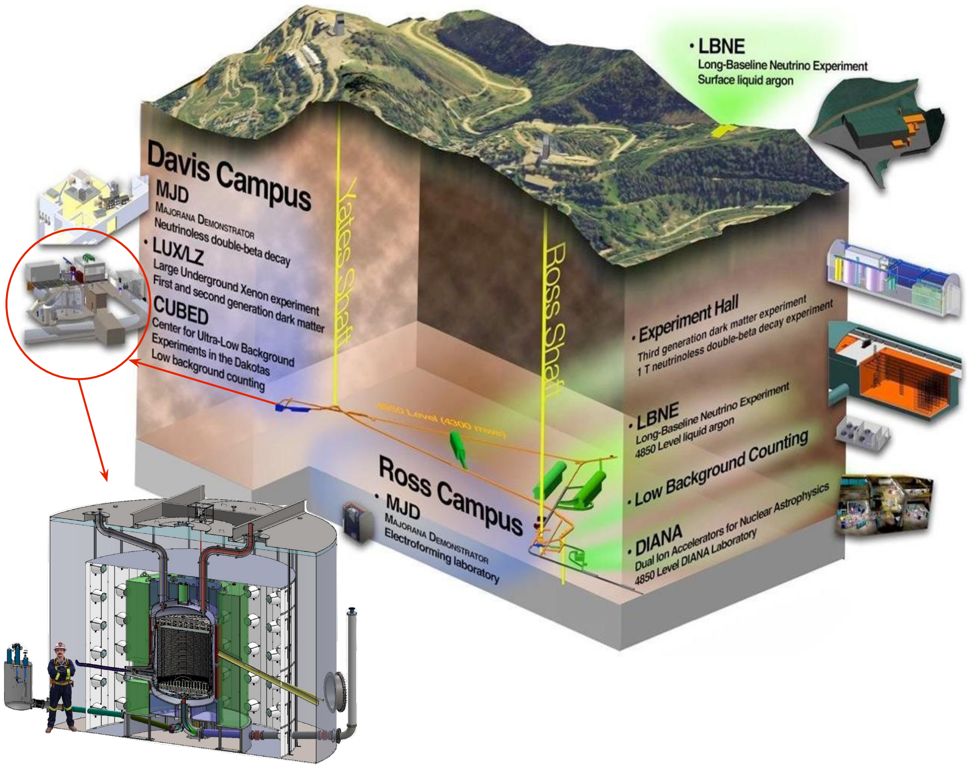
Muon Flux Measurements at Sanford Underground Research Facility with the LUX-ZEPLIN Experiment

Harvey Birch, on behalf of LUX-ZEPLIN Collaboration

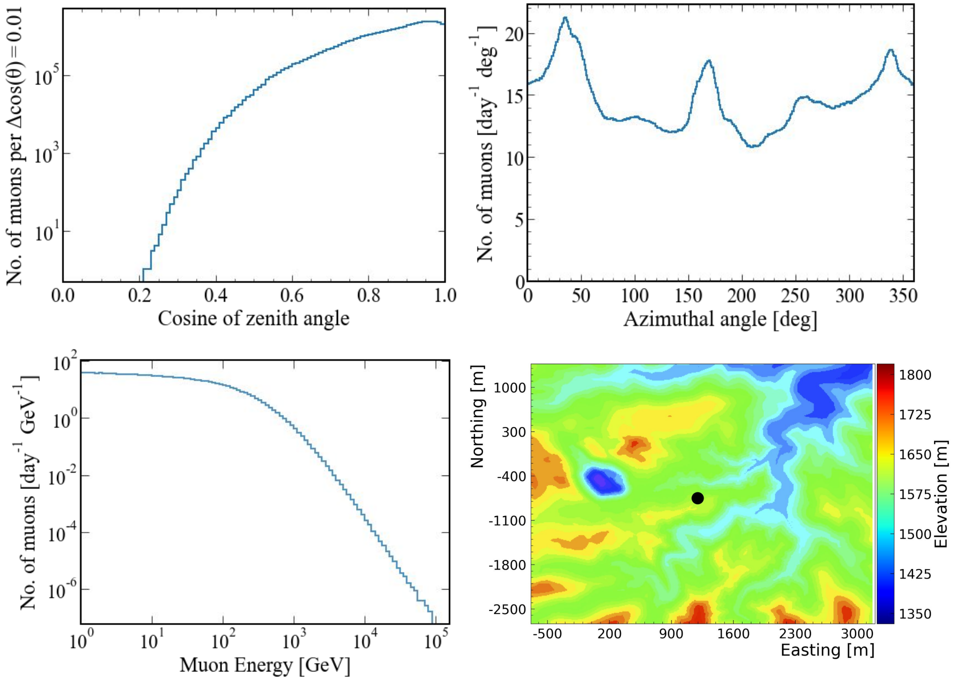
Young Scientists Forum, 59th Rencontres de Moriond 2025

The LUX-ZEPLIN Dark Matter Experiment and SURF

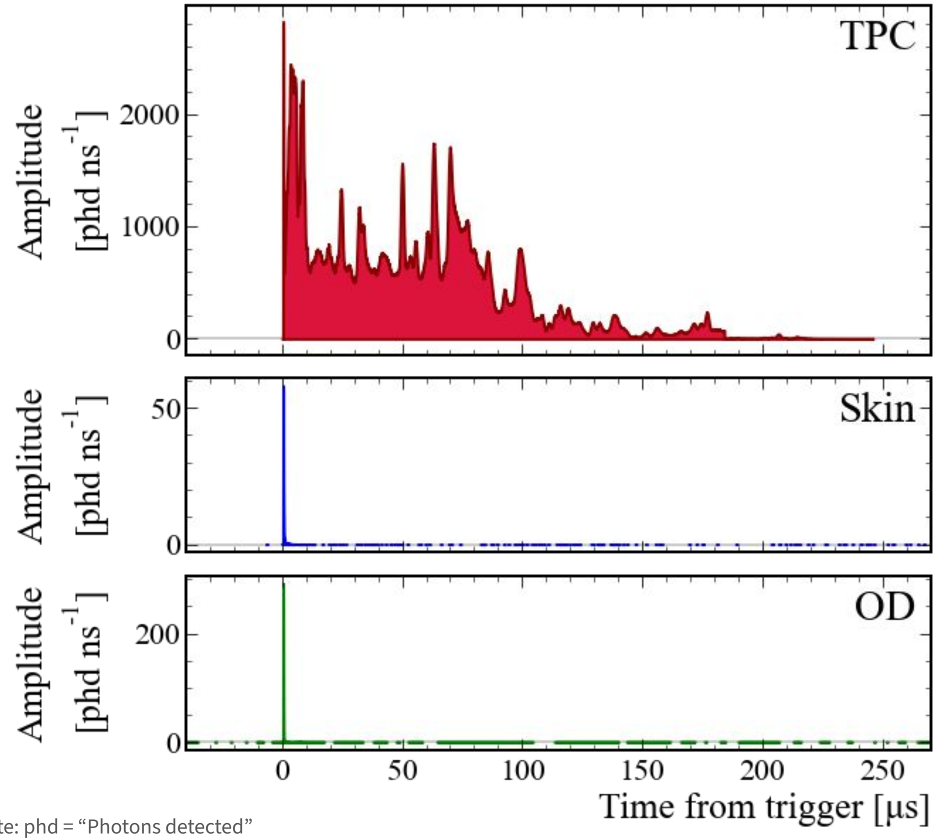
- The **L**UX-**Z**EPLIN (LZ) Dark Matter Experiment is situated in the Davis Cavern at the **S**anford **U**nderground **R**esearch **F**acility (SURF).
- LZ is second generation dark matter experiment.
- At the core of the experiment is a liquid xenon (LXe) time-projection chamber (TPC), 7t active volume.
- The TPC is surrounded by an active veto system:
  - Instrumented 2t LXe Skin Detector.
  - 17t GdLS instrumented Outer Detector submerged in 238t of ultrapure water.
- The detector is at a depth of 4300 m w.e.



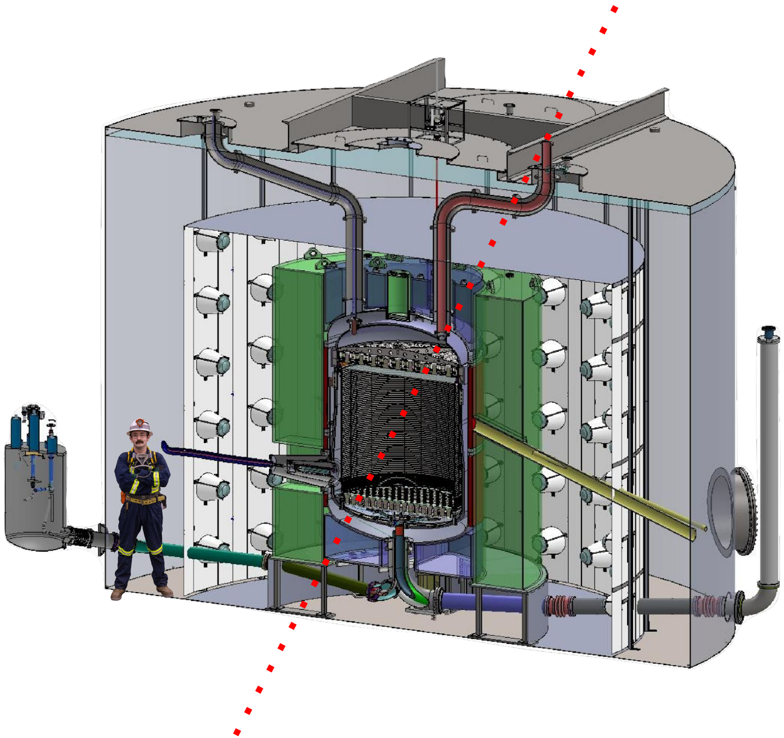
- Muon simulations carried out using MUSUN (**MU**on **S**imulations **UN**derground) code, GEANT4 based simulation.
- The code uses muon energy spectra and angular distributions in the Davis campus at SURF obtained with MUSIC (**MU**on **SI**mulation **C**ode).
- 4.82×10^{7} muons were propagated corresponding to a live time of 9147 days (0.0610 muons per second).
- The average density of rock was assumed to be 2.70 g cm^{-3} in the MUSIC simulation.
- The measurement of the muon flux with the veto system of the Majorana demonstrator suggest that the density may be larger (2.8-2.9 g cm^{-3})



What Does a Muon Look Like In LZ?

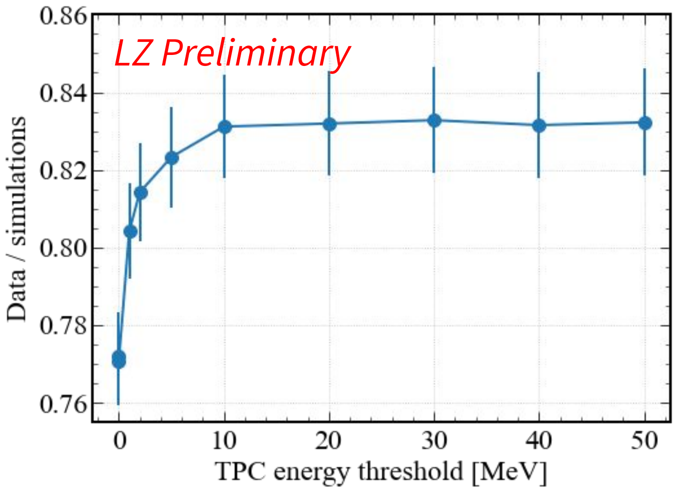


Note: phd = “Photons detected”



Data and Selection

- Analysed a 367 live-day exposure using LZ's WS2022 and WS2024 datasets.
- Timing selection:
  - Three different considerations were made:
    - OD pulse time - Skin pulse time (-200 → 200 ns)
    - Skin pulse time - TPC pulse time (-1200 → 200 ns)
    - OD pulse time - TPC pulse time (-1200 → 200 ns)
- Outer Detector Selection:
  - 8 MeV Energy Threshold to select events above Gadolinium Neutron Capture end point.
  - Pulse shape cut to remove spurious noise.
- TPC Energy Threshold:
  - 10 MeV Energy Threshold, determined using the ratio between the number of events data and simulation.



Muon Flux Reconstruction

- We have scaled the simulated muon flux by the same ratio as that for the measured-to-simulated daily rate.
- We have assumed that muon transport through the detector and detector response are simulated correctly by GEANT4.
- Using Eq. (1), the ratio of data to simulated data:

  $R_m / R_s = 0.831 \pm 0.013$ (stat.) $\pm\, 0.008$ (syst.)

  and from the simulated muon flux, F_s, of 6.16×10^{-9} cm^{-2} s^{-1}, we derive the reconstructed muon flux as:

  $F_m = (5.12 \pm 0.08$ (stat.) $\pm\, 0.05$ (syst.)$) \times 10^{-9}$ cm^{-2} s^{-1}

- This flux agrees with the Majorana measurement in the nearby cavern: $(5.31 \pm 0.17) \times 10^{-9}$ cm^{-2} s^{-1}.

$$F_m = F_s \times \frac{R_m}{R_s} \qquad (1)$$

F_m = measured muon flux through the surface of a sphere reconstructed from the measured rate

F_s = simulated muon flux through a surface of a sphere

R_m = measured muon rate through the detector

R_s = simulated muon rate through the detector

Summary

- We derive the reconstructed muon flux from the combined LZ WS2022 and WS2024 datasets rate measurement as:

  $F_m = (5.12 \pm 0.08\ (\text{stat.}) \pm 0.05\ (\text{syst.})) \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}$

- This flux agrees with the Majorana measurement in the nearby cavern:

  $F_m = (5.31 \pm 0.17) \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}$.

- We have evaluated the rock density above the Davis Cavern to be:

  $2.77 \pm 0.01\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{g cm}^{-3}$

Thank you for listening

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LZ (LUX-ZEPLIN) Collaboration, 38 Institutions, 250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
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See Sam Eriksen's talk "*Dark matter searches in the LZ experiment*" on Thursday for more results from LUX-ZEPLIN.

References

1. M. L. Cherry et al., **Multiple muons in the Homestake underground detector**, Phys. Rev. D 27 (1983) 1444–1447. doi:10.1103/PhysRevD.27.1444.

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4. P. Antonioli et al., **A three-dimensional code for muon propagation through the rock: MUSIC**, Astropart.Phys. 7 (1997) 357. doi:10.1016/s0927-6505(97)00035-2.

5. J. Heise, **The Sanford Underground Research Facility at Homestake**, Journal of Physics: Conference Series 606(2015) 012015. doi:10.1088/1742-6596/606/1/012015.

6. M. Adrover, et al., **Cosmogenic background simulations for neutrinoless double beta decay with the DARWIN observatory at various underground sites**, Eur. Phys. J. C 84 (1) (2024) 88. arXiv:2306.16340,doi:10.1140/epjc/s10052-023-12298-w

Backup

Atmospheric Muon Production & Backgrounds

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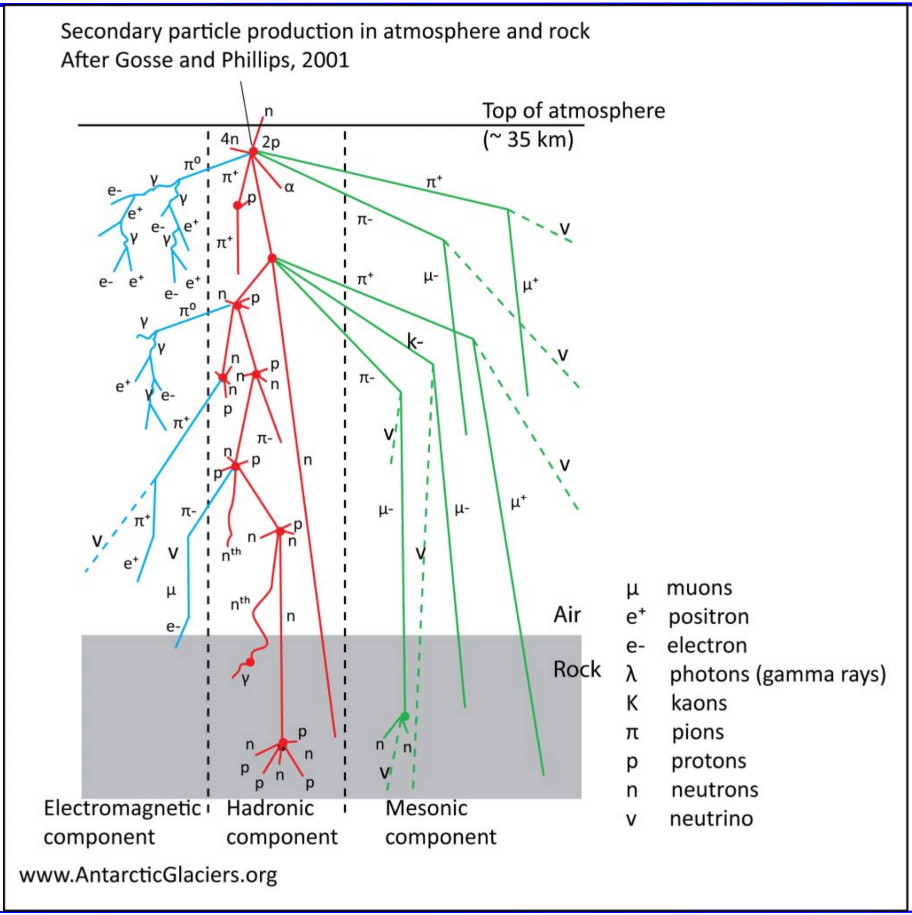
- Atmospheric showers result from the collision of cosmic rays with the upper atmosphere.
- The collisions generate a cascade of secondaries that decay.
- Bulk of the secondaries are pions and kaons that decay into muons.
- Due to time-dilation, many of the muons reach the Earth's surface.
- Muons can interact with detector materials and generate neutrons.
- Low-background experiments utilize the rock burdens to mitigate the effect of muons on experiments.

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

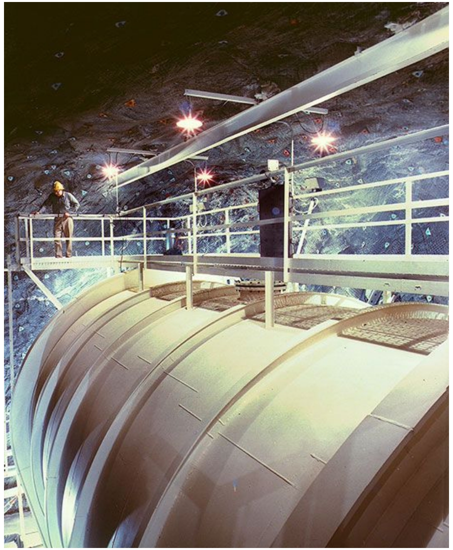
$$\mu^- + A \rightarrow A' + n$$

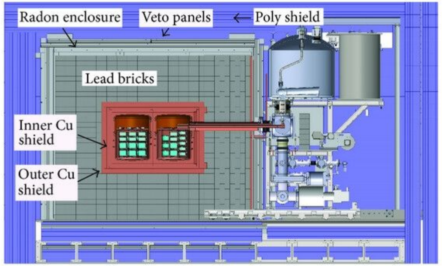
Atmospheric Muon Production



Previous Measurements at SURF

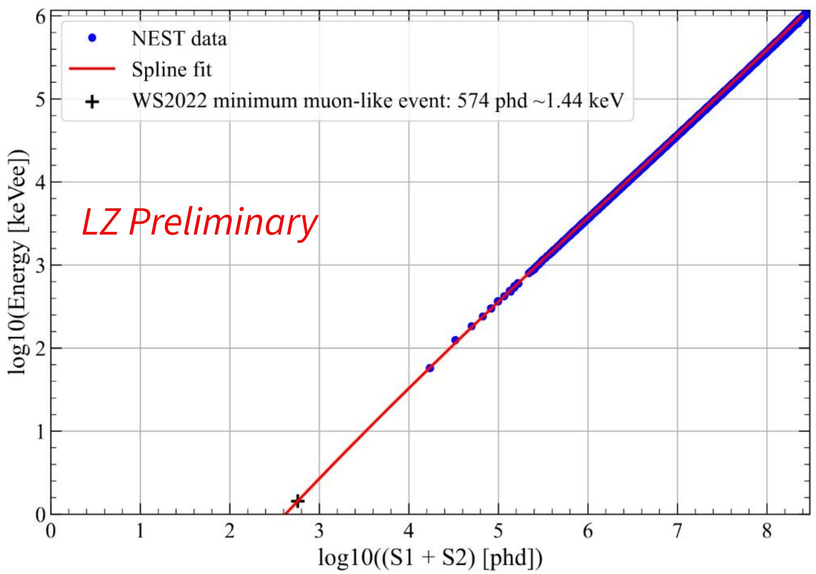
- Vertical muon intensity has been measured by the veto system of the chlorine solar neutrino experiment giving the value of $(5.38 \pm 0.07) \times 10^{-9}$ muons s^{-1} cm^{-2} sr^{-1}.
- Our model prediction of vertical muon intensity: 5.18×10^{-9} muons s^{-1} cm^{-2} sr^{-1}
- More recently the total muon flux was measured by the veto system of the Majorana demonstrator to be $(5.31 \pm 0.17) \times 10^{-9}$ muons s^{-1} cm^{-2}.
- Our model predicts a total muon flux at 6.16×10^{-9} muons s^{-1} cm^{-2}.
- Our goal was to use the measurements of muon rate and flux to re-normalise the muon model and estimate the average rock density above the lab, assuming it is uniform through zenith angles 0-90°.





TPC Energy to Light Conversion - NEST

- Produced simulations using the **N**oble **E**lement **S**imulation **T**echnique (NEST) inputting position information from GEANT4 simulations.
- NEST has a MIP module which using linear energy transfer to simulate a muon.
- For a muon with a mean energy of 283 GeV in xenon, this is 2.1 MeV cm^2 g^{-1}.
- NEST outputs the energy, total S1 light and total S2 light. Here, the S1 and S2 light was summed.
- The spline fit was then used to convert the Total Pulse Area observed in a muon event window to energy.



Muon Flux Dependence on Rock Density

- The difference in the reconstructed and simulated muon fluxes is primarily due to difference in rock density compared with the initial muon model.
- The simulated flux matched the measured one with an average rock density of (2.78 ± 0.01) g cm^{-3} when using average rock composition parameters from one geology study.
- From a separate geology report, we used average Z and A parameters from a type of rock called Yates Amphibolite.
    - With these values the simulated flux matched the measured one with an average rock density of (2.76 ± 0.01) g cm^{-3} .
- The average of these is 2.77 ± 0.01 (stat.) ± 0.01 (syst.) g cm^{-3} which is 3.0 % higher than the initial muon model assumption, but lower than that reported by SURF ((2.89 ± 0.06) g cm^{-3}).