# Design Studies for the Upcoming Prototype GRAMS Balloon Flight
# REU Program at Columbia University - Nevis Labs


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**Abstract**

GRAMS (Gamma-Ray and Anti-matter Annihilation Survey) will search for both MeV gamma-rays and indirect dark matter signatures using antideuterons and antihelium. The detector will be a novel LArTPC (Liquid Argon Time Projection Chamber), with a prototype balloon flight expected to fly at the end of 2025 in Arizona. After the prototype flight, GRAMS will be either a balloon or satellite mission. In this report, events will be simulated using GramsSim, a simulation software that is being developed for GRAMS. The analysis of this simulation data will help develop the necessary electronics for the data acquisition system (DAQ). In addition, it will be a proof of concept for the physics goals for the future balloon/satellite mission.

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# 1 Introduction

## 1.1 GRAMS and pGRAMS Detector

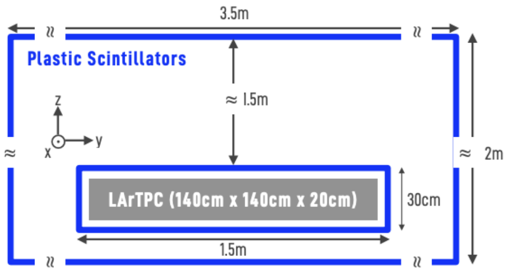



***Figure 1:*** *Detector design schematic for GRAMS (pGRAMS will be smaller)*

The pGRAMS detector, a balloon-based LArTPC (Liquid Argon Time Projection Chamber), with dimensions 30 cm $\times 30cmx20cm.Thedetectorwillbesurroundedby TOF (Time of Flight) plasticscintillat$ $bornesystem. However, theanalysisworkdoneforpGRAMSwillalsoapplytoGRAMS, whichwillbealargerde$ $raydetectorinflight.$

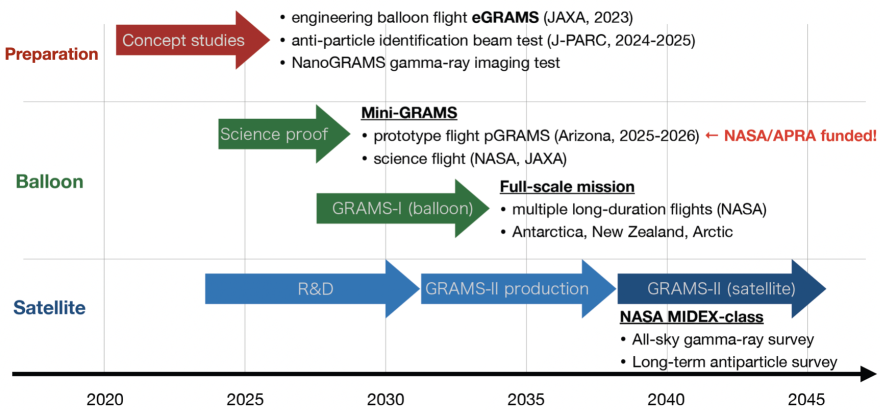



***Figure 3:*** *GRAMS experiment timeline so far pGRAMS is being developed to prove gamma-ray data can be successfully collected.*

## 1.2 LArTPC

The LArTPC is a cost-effective detector that has been proven effective in neutrino and dark matter experiments [Acciarri(2017)]. A LArTPC works by detecting charged particles within the detector. When an incoming particle interacts with an Argon atom, it ionizes electrons (and can produce other charged particles as well). The uniform electric field in the detector drifts the ionized electrons toward the readout anode. The wire strips on the anode provide the x and y position information of the ionized electron clusters. Using the known value of the drift velocity, the distance in the z direction can be calculated. Since the drift velocity is constant and the time is determined from the scintillation light, the z position is given by the drift velocity multiplied by the relative time. Knowing the z position allows for events to be reconstructed in three dimensions, providing a wide field of view by detecting gamma rays from any direction. This is one of the advantages of using a LArTPC detector instead of semiconductors or scintillators, as in previous Compton telescopes. A LArTPC detector has high collection efficiency because Argon is dense, meaning particles are less likely to pass through undetected. The three-dimensional reconstruction

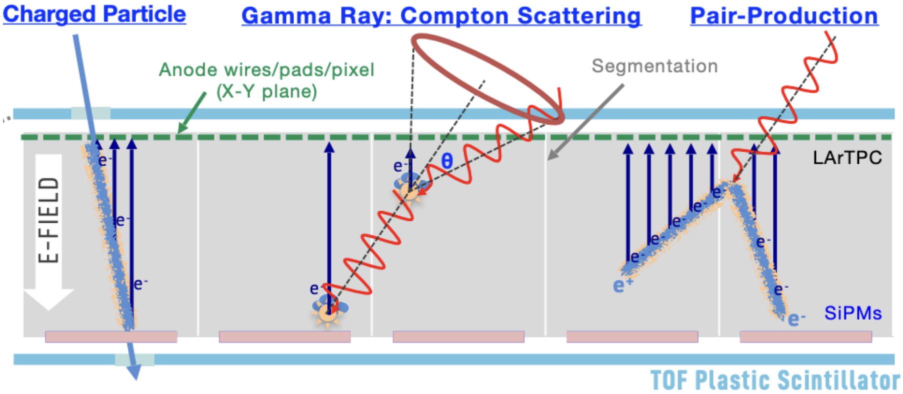



***Figure 4:*** *LArTPC Diagram that demonstrate how a LArTPC works*

is achieved by analyzing the low-energy ionization electrons produced by the incoming particle's interaction with the liquid Argon.

## 1.3 Science Motivation

There is a lack of observations of gamma rays in the MeV energy range. Previous experiments had low sensitivity to MeV energies and had to focus on gamma rays with higher fluxes to compensate. One advantage of GRAMS is its ability to search for gamma rays in the MeV range at lower fluxes, thanks to the higher sensitivity of its detector. Studying gamma rays in this range will increase the sensitivity of observations by an order of magnitude. The GRAMS experiment is still in its early stages, and the large-scale detector is under development. In 2023, an engineering flight (eGRAMS) in Japan successfully demonstrated that a LArTPC can operate in space. The next step is pGRAMS (p for prototype), scheduled for launch in 2025, which will serve as a full-detector proof of concept. This balloon launch will verify the electronics' ability to record data by measuring known fluxes and using a stable gamma source within the detector to ensure accurate gamma-ray detection. The final GRAMS mission, planned for between 2030 and 2040, will be a larger balloon or satellite mission. Currently, GRAMS is in the research and development phase for the pGRAMS prototype flight. This flight will demonstrate proof of concept by showing that data can be collected and analyzed to reconstruct gamma rays in the MeV range during flight. With pGRAMS expected to launch in late 2025, it is crucial to finalize calculations for the readout system. Accurate simulations and calculations will help validate and optimize the pGRAMS readout design.

## 1.4 Detecting Gamma-Rays

In order to detect gamma-rays, we will focus on Compton scattering. In the MeV energy range, gamma rays tend to Compton scatter [Tanabashi(2018)], so GRAMS will be able to observe many of these events. When a gamma ray undergoes a Compton scatter, it interacts producing a Compton electron, which travels through the detector and ionizes other Argon atoms, producing ionized electrons **??**. These ionized electrons have low energy and will drift toward the readout anode to be detected. Since photons are neutral particles, we track the charged particles (in this case, Compton electrons), specifically the ionization electrons they produce, to reconstruct an event. If two or more Compton scatters occur, a 'Compton cone' can be reconstructed. This cone represents the possible directions of the incoming gamma-ray source. With three or more Compton cones, the direction of the incoming gamma-ray can be determined.

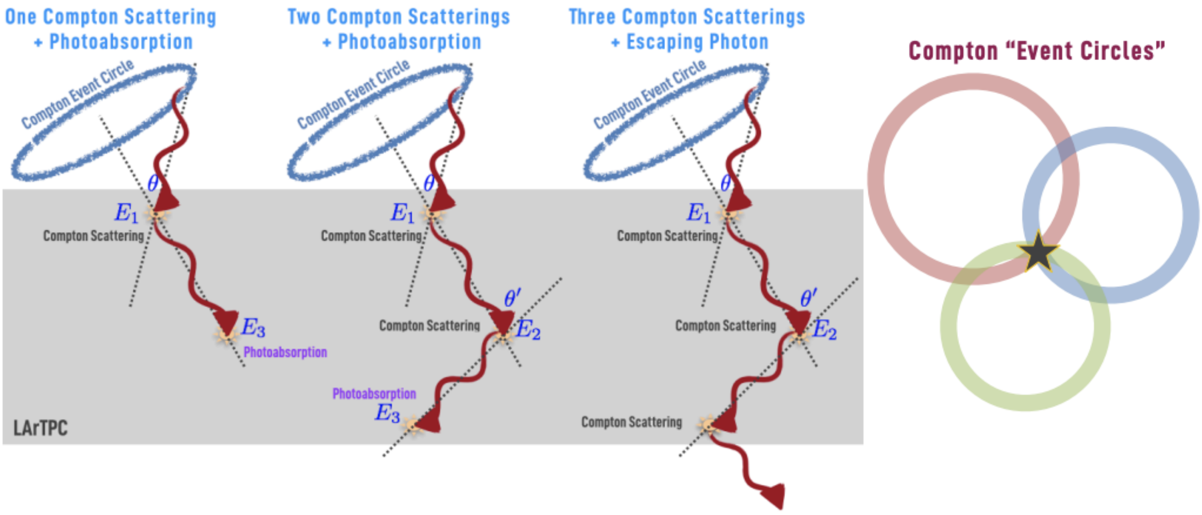



***Figure 5:*** *The event circles will provide the information of the cosmic ray source*

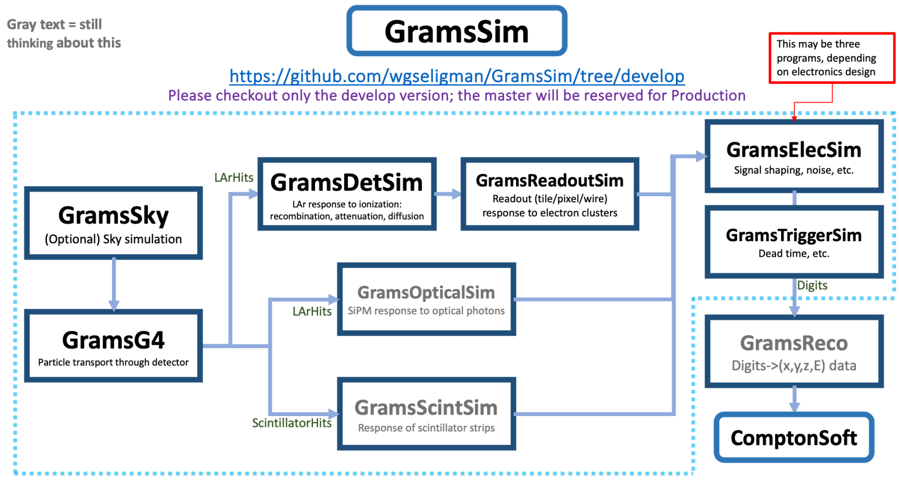



***Figure 6:*** *Different stages of GramsSim, the simulation software that was developed for the GRAMS experiment. The simulation outputs data for GramsG4, GramsDetSim, GramsReaoutSim, and GramsElecSim. In this report data all of these output files were used.*

## 1.5 Simulation Software

For this report, all simulations were performed using GramsSim, a simulation software developed for GRAMS [Seligman(2021)]. The software is divided into different stages, each handling a specific part of the event simulation process. The first step is to specify the type of incoming particle, the energy range, and the number of particles to be generated within the GRAMS or pGRAMS detector geometry. After generating the events, the simulation proceeds using the Geant4 particle source, modeled for the specific detector geometry. The Geant4 (also called G4) stage simulates the charged particles as they propagate through the detector, including the incoming particle and those produced due to interactions within the detector.

The next step is to run the detector simulation, which uses the G4 simulation but incorporates the geometry of the detector. The detector simulation groups the electrons into electron clusters and accounts for detector effects such as absorption, recombination, and diffusion. Once the detector simulation is complete, we move on to the readout simulation. This step assigns a pixel ID to the x and y positions of the readout anode using the electron clusters from the detector simulation. The final step (for this project) is running the electronics simulation, which takes the output from the readout and detector simulations to create analog and digital waveforms.

# 2 Design Studies

## 2.1 Project Motivation

For this project, an end-to-end check of the simulation software up to the readout stage of the detector needs to be performed to validate the data. This is one of the initial steps required to ensure that the calculations for pGRAMS and future GRAMS missions are as accurate as possible. Fine-tuning the GramsSim software will help validate and optimize the design of the readout system and the data acquisition (DAQ) for both pGRAMS and the future GRAMS balloon/satellite science mission. The simulation software will provide crucial information for signal shaping, triggering rates, occupancy, and hit rates, all of which are essential for calculating the data rates for pGRAMS.

Another important aspect of this project is ensuring that the simulation outputs make physical sense. The correctness of the data can be verified by comparing the known flux values of different particles for the specific altitude at which pGRAMS will be operating. Confirming the accuracy of the simulation data will allow us to calculate the expected rate of incoming particles and the hit occupancy when pGRAMS is in flight.

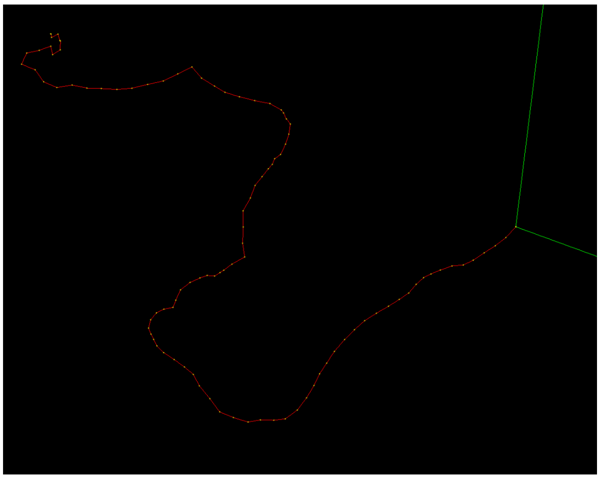
## 2.2 Methodology

As mentioned above, the first step was to generate events for specific particles within a specified energy range. The particles of interest in this report include photons, electrons, positrons, protons, and alpha particles. In the future, this methodology can be extended to other particles as well. Initially, 10,000 events were generated with an energy range of 0.05–200 MeV, using a power-law distribution and an isotropic distribution for the incoming particle direction relative to the detector. The pGRAMS LArTPC will have dimensions of 30 cm x 30 cm x 20 cm, and the 10,000 events were injected from all directions into the geometry of this detector. Although this report focuses on pGRAMS, the same methodology can be applied for future GRAMS as well.
GramsSim definitions

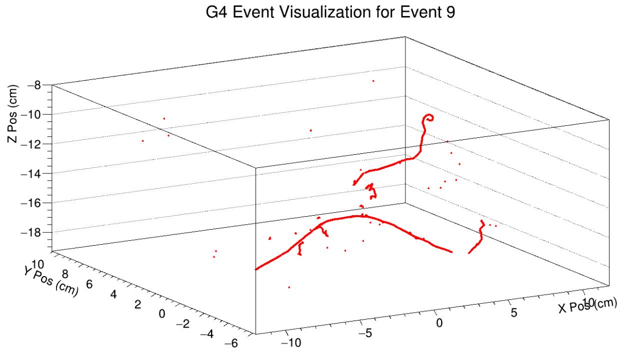
- Event- the information associated with a single incoming particle.
- Track- the particle trajectory.
- Hit- it is the recorded "step" (each step size).

## 2.3 Geant4 Simulation

Using the Geant4 particle simulation software, we obtain the truth-level information of the events. This includes the energy of the primary particle, track ID, hit ID, position, time, and momentum. The truth-level information from the Geant4 simulation is broken down into three stages: 1. MCTrackList, which includes all the events before they reach the readout anode (HitIDs haven't been assigned at this stage yet); 2. MCLArHits, the second stage, which provides the truth-level information for the events that contain tracks that reach the readout anode, their respective ionization energy deposits, and HitIDs are assigned; and 3. MCScintHits, which contains the truth-level information for the events that deposit ionization energy in the scintillator strips. In this analysis, MCScintHits was not used. In the future, data from all three outputs can be compared for analysis. One of the first steps taken to understand the output of the simulation was to create a three-dimensional visualization of what a track looks like in the detector using MCLArHits



*(a) Zoomed in example of an ionized electron track, the green line is a Compton scatter photon, the red lines are the track of a Compton electron, and the yellow dots are the step size (the maximum step size is 0.2mm).*




*(b) Event visualization using the information from MCLArHits. The x, y, and z position was used to verify the that the events are within the detector geometry bounds. For this event visualization the ionized electrons drift upwards.*

***Figure 7:*** *Figure a. shows a zoomed in track of an event genrated by Geant4. Figure b. is an event visualization during the same simulation stage.*

## 2.4 Detector Simulation

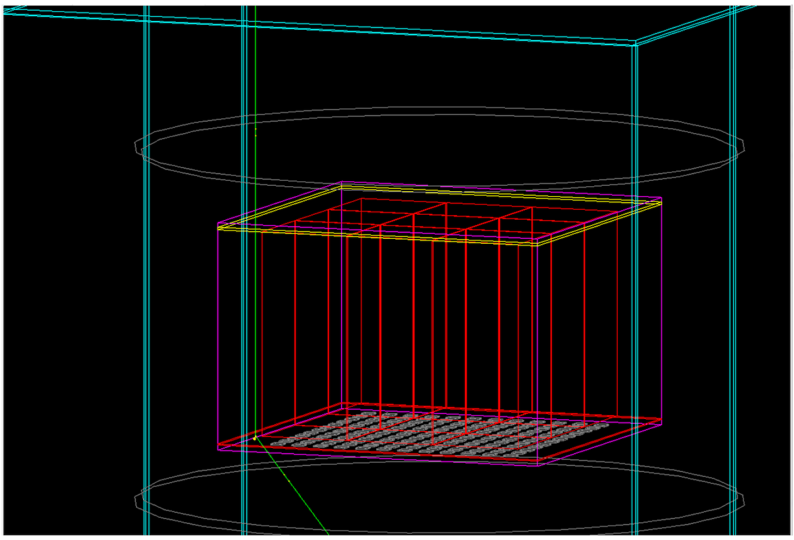


***Figure 8:*** *This image is an example of what an event would look like in the detector. The green line represents a neutral particle, in this case a photon.*

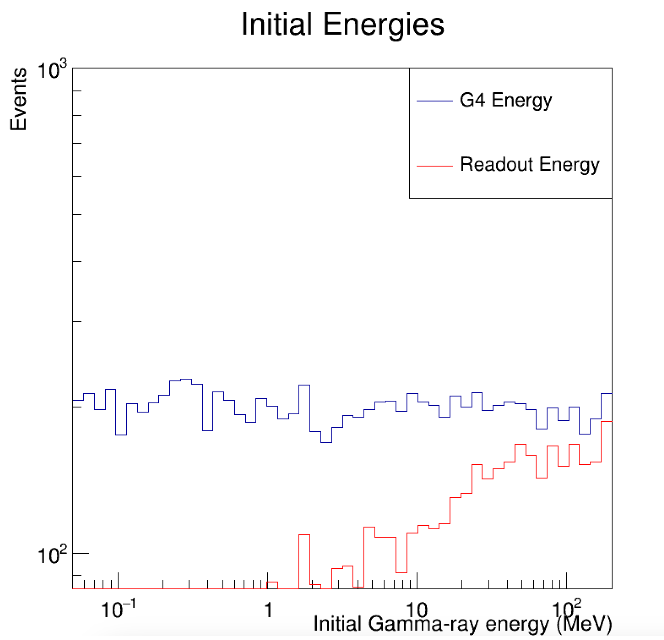



***Figure 9:*** *Energy count comparison using the Geant4 output during the MCTrackList stage (all the events are accounted for during this stage). The red line is the energy count of the initial gamma-ray energy for the events that deposit ionization energy to the readout anode.*

The detector simulation is generated using the output from the Geant4 simulation. The purpose of the detector simulation software is to model the particles within the GRAMS geometry and simulate their ionization through the detector. During this stage, three detector models are applied to the ionization electrons. The first model is recombination, which simulates the absorption of ionized electrons by the liquid Argon atoms. The second model is absorption, which simulates the absorption effects due to impurities in the Argon. Lastly, the diffusion model is applied; this model does not affect the energy of the ionized electrons but simulates how much they spread as they drift towards the anode. These three models collectively provide the energy of the ionized electrons that reach the readout anode. It is crucial to account for these effects, as not all ionized electrons will reach the anode, and some will lose energy during drift. Once these models are considered, the energy of the ionized electrons from the Geant4 simulation can be compared to the energy recorded by the detector. Comparing the energies manually is a good way to verify that the simulation is functioning correctly. Additionally, at this stage, a three-dimensional event can be visualized. To achieve a complete three-dimensional reconstruction, the drift time will be used as the z position.

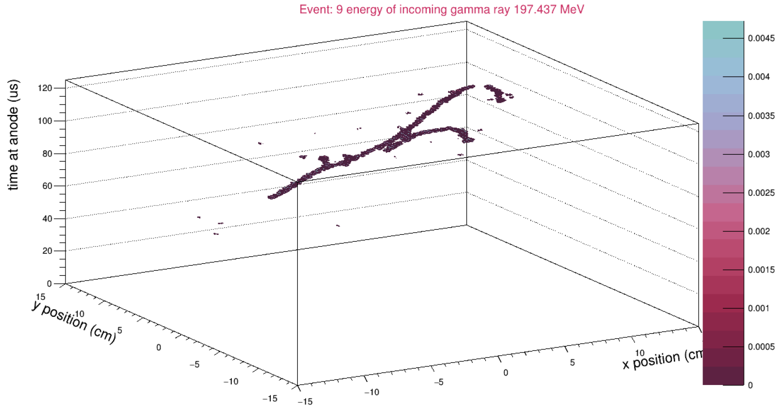



***Figure 10:*** *Event reconstruction using the x and y position from the readout anode, the z axis is the drift time which can be calculates using the drift distance along z and the drift velocity which is constant. In this case the z axis is inverted, for the prototype flight the axis should be going from 125μs to 0.*

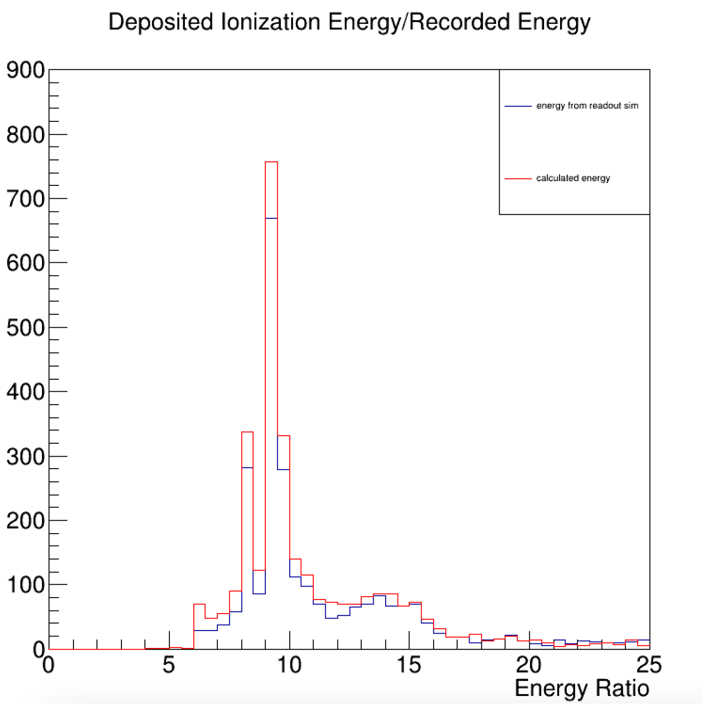



***Figure 11:*** *Using the energy during the Geant4 stage the energy readout at the anode can be calculated using the detector models. The red line is the calculated energy at readout and the blue line is the energy the simulation outputs at the readout stage. This histogram is a ratio of the Geant4 energy divided by the analytical calculation of the energy at the anode or divided by the detected energy at the anode*

## 2.5 Readout Simulation

Using the output from the detector simulation, the readout simulation groups the electrons into clusters. The clusters that reach the anode are assigned a pixel ID for the x and y positions. In this report, the readout anode measure 30 cm x 30 cm. Each wire strip is 2 mm pitch, so the anode will have 150 channels (pixels) in the x direction and 150 in the y direction, totaling 300 channels. For pGRAMS the wire strips will be approximately 3.3mm pitch, therefore the anode will have 180 channels total. For the future GRAMS mission, the readout anode will consist of pixels instead of wires, which will allow for more precise localization of the detected ionization electrons. Using this positional information and the energy recorded at the anode, a two-dimensional reconstruction of the readout anode can be performed to better understand what the event projection at the anode would look like 12.

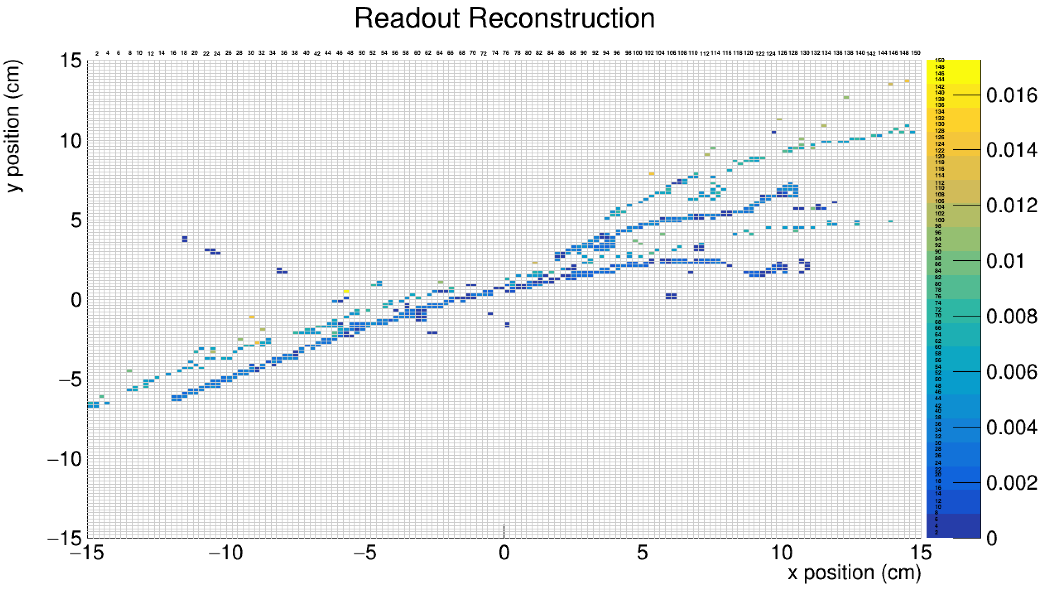


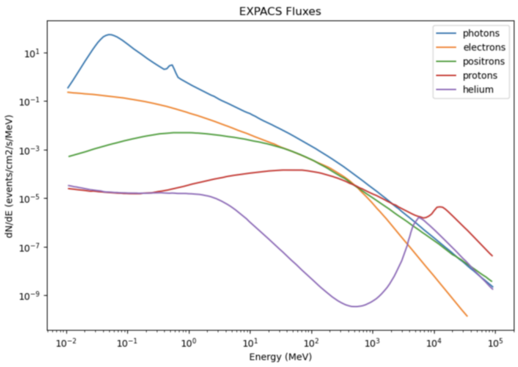

***Figure 12:*** *This is a two dimensional reconstruction of the electron clusters that deposit energy to the anode. Each pixel represents a channel of the readout anode, the color scale represents the energy of the ionized electrons in MeV*

After the two-dimensional reconstruction was completed, the number of hits versus time was plotted to compare it with the known flux values. Up to this point, the simulation software was compared to manually performed calculations. After verifying that these were correct, the same check was conducted for other particles, including protons, positrons, electrons, and alpha particles. Verifying the expected flux values is an effective way to ensure that the simulation is functioning correctly. Knowing that the software processes data accurately will allow us to calculate the necessary storage space required with certainty. Additionally, once pGRAMS is launched, it will collect data and verify that the observed flux values match the expected numbers.

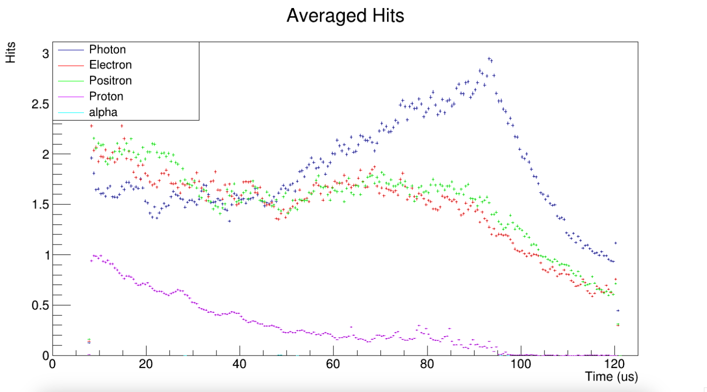
## 2.6 Electronics Simulation

During the electronics simulation stage, the response of the electronics, noise, and shaping of the detector readout are generated. The simulation uses the output from the detector and readout simulations to create both analog and digital waveforms. This is done by convolving the charge depositions with an electronics response function. Using the digital waveform values, the hit rate can be calculated by counting the non-zero ADC values and dividing this number by the total number of ADC values (including zero values). However, the electronics simulation requires further development, as the correct response function is not yet fully characterized. Additionally, the electric field response and electronics noise must be implemented. Parameters such as rise and decay times, the general pulse shape, and the noise floor need to be fully characterized to produce better waveforms, which are necessary for accurate occupancy studies and trigger rate calculations.

# 3 Results




***(a)*** *Expected fluxes using the EXPACS simulation data at a height of 30km.*




***(b)*** *Number of Hits vs Time. The hits are averaged by the total number of hits.*

***Figure 13:*** *The averaged number of hits can provide a sense of how the particles interact through the detector. Massive particles are less likely to make it through the detector. In this figure the particles are drifting from the right side to left. When the time is zero it the electron clusters made it to the readout anode.*

At this point, all stages of the simulation have been completed. Having this information is crucial for determining the data rates, required disk space, and expected hit rates during pGRAMS operation. The averaged hit plot **??** provides the necessary data to estimate the expected hit rate for pGRAMS. In this report, the electron lifetime was set to 50,000 ns, which is short for the size of the detector. This is reflected in the plot of the Geant4 energy divided by the analytical calculation of energy after the detector models are applied. With a 50,000 ns lifetime, the detector is able to detect about 1/10 of the events that deposit ionization energy 11. In the future, this value can be adjusted to a larger time to yield more sensible results.

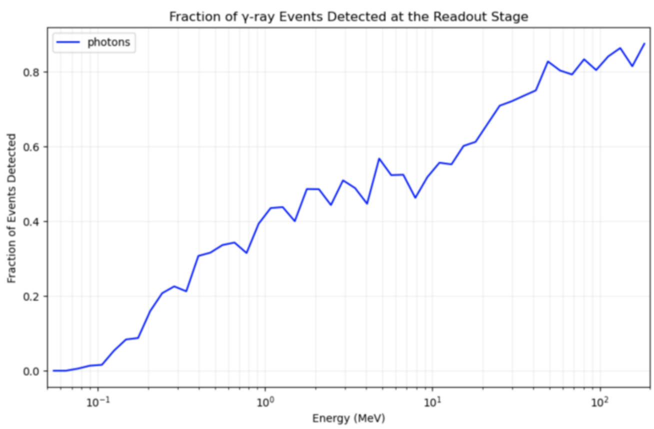



***Figure 14:*** *Using the initial energy of the incoming gamma-ray, we can see how many events make it to the anode so the event can be reconstructed. In this figure the ratio is the events from the Geant4 stage divide by events that make to the readout anode from ReadoutSim.*

# 4 Summary and Conclusions

## 4.1 Conclusion

An end to end check for GramsSim was performed during this project. Additionally, the necessary tools to calculate readout metrics were developed, these will be used to fine tune the readout electronics and DAQ for pGRAMS and future GRAMS readout system. A full simulation study chain of the ionization electrons at different stages was developed as well as an event visualization for Geant4 and event reconstruction for the detector and readout stage. Using this simulation study chain other particles can be analyzed as well using the EXPACS [Agency(2024)] expected flux. For the purpose of this project all the particles generated had a power law energy distribution of $E^{-}1$.

## 4.2 Next Steps

In the future the simulation sample size needs to be bigger in order to obtain more accurate results through higher statistics.
The electronics simulation code needs to be reworked and developed to account the electric field response as well as the response function for the readout electronics.
The injection of particles in the detector needs to be investigated more thoroughly, especially for massive particles. As it was previously shown massive particles like the alpha particle are barely detected in the simulation.
After implementing the changes to the electronics simulation, waveforms can be produced using the analog charge.
So far muons haven't been mentioned even though they can be detected at the altitude pGRAMS will be flown, this is because the simulation uses the total energy (kinetic + rest energy), therefore having low energies for a massive particle cannot be generated. For this reason the Geant4 stage needs to be tuned a bit more.

# 5 Acknowledgements

I would like to thank Prof. Georgia Karagiorgi, Prof . Reshmi Mukherjee, Dr. Ibrahim Safa, Dr. Akshay Malige, Dr. William Seligman, and Svanik Tandon for their guidance and support. This material is based upon work supported by the National Science Foundation under Grant No. PHY-2349438.

# A Apendix

## A.1 Detector Models

### A.1.1 Recombination

- $\beta'$, $\alpha$, $A_B$, and $k_B$ are material- and detector-based parameters that must be measured empirically [Acciarri(2013)] [S. Amoruso(2004)];
- $\epsilon$ is the electric field.
- $\xi$ is the effective electric field.
- $\rho$ is the density of the liquid argon.
- $\frac{dE}{dx}$ is the ionization energy per unit length.

$$\xi = \frac{\beta' \frac{dE}{dx}}{\rho\epsilon} \tag{1}$$

$$R_{\text{Box}} = \frac{1}{\xi}\ln(\alpha + \xi) \tag{2}$$

### A.1.2 Absorption

- $s_{\text{drift}}$ is the drift distance between the ionization hit in the TPC to the anode.
- $v_{\text{drift}}$ is the drift velocity.
- $t_{\text{elec}}$ is the electron lifetime in the liquid argon.

$$t_{\text{drift}} = \frac{s_{\text{drift}}}{v_{\text{drift}}} \tag{3}$$

$$R_{\text{abs}} = e^{-t_{\text{drift}}/t_{\text{elec}}} \tag{4}$$

## Transverse Diffusion

$$D_T = \frac{kT}{\mu} \tag{5}$$

where:

- $kT = 0.0075\,\text{eV}$ for argon at the normal boiling point (87.3 K).
- $e$ is the electron charge.
- $\mu$ is the electron mobility, which is the electron drift velocity $v$ per unit electric field $E$.

# References


[Acciarri(2013)] et al Acciarri. A study of electron recombination using highly ionizing particles in the argoneut liquid argon tpc. *Journal of Instrumentation*, 8(08):P08005–P08005, August 2013. ISSN 1748-0221. doi: 10.1088/1748-0221/8/08/p08005. URL `http://dx.doi.org/10.1088/1748-0221/8/08/P08005`.

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