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Cosmic muon simulation with a new HCal prototype geometry at LDMX

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Abstract

The light dark matter experiment (LDMX) is a planned experiment to search for dark matter (DM) in the partly unexplored lower region of the mass range motivated by the thermal freeze-out mechanism. Electrons will be accelerated toward a tungsten target, and as they scatter off a nucleus, production of DM may occur, which will be inferred from a significant amount of missing energy in the detector. Therefore, a detector capable of detecting and measuring all incoming and outgoing particles, together with a thorough understanding of its performance, is necessary. Measurements, as well as simulations, of cosmic muon interactions with prototypes of the detector's different subsystems is one approach that will contribute to a deeper understanding.

The aim of this thesis is to create a geometry description of the hadronic calorimeter (HCal) components of a test-stand that will be used for cosmic-muon measurements, integrate it into the LDMX software framework, and simulate cosmic muons passing through it. The work carried out in this project includes the description of the HCal prototype geometry in a GDML file, adaptation of a Python file that supplies detector information to the software, and modifications of the employed cosmic muon generator. Data obtained directly from simulation and after mimicking real data acquisition are analyzed. When the new geometry is incorporated into the software, data received directly from simulation provide reasonable results, while issues appear to arise in the digitization or reconstruction process. In addition, different parts of the detector are observed to receive an unequal amount of hits. Most likely, more changes must be made to the software to successfully digitize and reconstruct the simulated data obtained when using the new geometry.

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Finally, a special thank you to Lucia for accompanying me on this journey.

Abbreviations

DM	D ark M atter
SM	S tandard M odel
LDMX	the L ight D ark M atter eX periment
MIP	M inimally I onizing P article
MIM	M inimally I onizing M uon
HCal	H adronic C alorimeter
ECal	E lectromagnetic C alorimeter
Geant4	G eometry a nd t racking version 4
GDML	G eometry D escription M arkup L anguage

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1 Introduction

Multiple observations of the dynamics and structures of the universe, such as the rotational velocities of galaxies and galaxy clusters, suggest that the universe consists of only a small fraction of visible matter. The remaining mass cannot be observed with telescopes and is therefore called dark matter (DM). DM has become a large field in particle physics and theories about its origin suggest that it could be created in accelerator-based experiments and possess a mass roughly between 1 MeV and 100 TeV [1]. Searches for particles that could constitute DM have been ongoing for many years, specifically in the larger mass range [2]. However, due to the absence of detection of any such particles, attention has slowly shifted toward the lower mass range. Unraveling this regime is what the light dark matter experiment (LDMX) plans to do.

By directing low-intensity bunches of electrons at a fixed tungsten target, LDMX hopes to produce DM, which will be identified by missing momentum. The detector is optimized to detect all particles that pass through it with subsystems such as trackers, an electromagnetic calorimeter (ECal), and a hadronic calorimeter (HCal) [3].

One of LDMX's upcoming projects is to measure cosmic muons in a setup of prototypes of the detectors various subsystems. Cosmic muons continuously reach the surface of the Earth, and most of them are close to minimally ionizing particles (MIPs). This property means that most of them will deposit nearly the same energy in the detector, despite variations in their initial energy, making them well suited for calibration and testing of detectors. Measuring cosmic muons with prototypes of the detector will provide valuable information about the detector performance, as well as how to operate the different systems together.

This project focuses on the simulation of one of the subsystems, the HCal. In particular, it aims to incorporate a representation of the HCal prototype geometry into the LDMX software. In addition, cosmic muon simulations are conducted and the resulting interactions are investigated to verify if the geometry description has been successfully included.

2 Background

2.1 Dark Matter

2.1.1 A brief history

In the 1930s, astronomers began to realize that there is not enough visible matter to explain the dynamics of galaxies and galaxy clusters and that there must exist some additional invisible mass. One of the earliest pieces of evidence was discovered when Knut Lundmark estimated seemingly unrealistically high mass-to-light ratios of multiple galaxies. Shortly thereafter, Fritz Zwicky found that the average velocity of galaxies in the Coma Cluster was much higher than could be justified by the observable mass. With no additional matter, the galaxies should escape the gravitational pull of the cluster. At first, many astronomers were skeptical of these findings, but observations of galactic rotation curves provided further evidence. From the distribution of visible matter, the rotational velocity is expected to decrease at larger radii. Instead, it remains nearly constant, indicating a considerable amount of missing matter within the galaxies [4].

Throughout the years, many theories have been proposed to explain this mass discrepancy. An early belief among many astronomers was that the dark mass could consist of low-luminescence objects such as planets, red dwarfs, and black holes. However, this was ruled out when measurements of the cosmic microwave background revealed that baryons could account for only a fraction of the matter of the universe. Efforts have also been made to modify Newtonian dynamics, which has resulted in successful descriptions of many spiral galaxies, but at the scale of galaxy clusters it is inadequate [4]. It has gradually become clear that the most likely explanation for DM is that it is composed of one or more undiscovered particle species.

2.1.2 Thermal relic dark matter

One particular mechanism explaining the origin of DM is the so-called thermal freeze-out. This scenario assumes that DM and SM particles annihilated into each other in the early universe. These interactions occurred at a rate faster than the expansion of the universe, leading to thermal equilibrium between the two sectors. As the universe expanded and cooled, pair production of DM particles became energetically inaccessible, and the DM density decreased. Once annihilation of the DM particles no longer occurred fast enough, the thermal equilibrium ceased, causing the abundance of DM to "freeze out" [5]. The resulting relic abundance depends on the interaction cross section and the mass of the DM particle. A weaker interaction would cause the freeze-out to happen earlier, leading to a higher relic abundance and vice-versa. Therefore, this theory places constraints on the DM particle and implies a possible mass range of roughly 1 MeV to 100 TeV [1][5]. Most searches for dark matter have been conducted in the upper half of this mass range, specifically searches for weakly interacting massive particles (WIMPs's). These particles are predicted to have masses between approximately 10 GeV to 1 TeV [6], which coincides with energy scales accessible at most accelerator-based experiments. However, such particles have not yet been detected, which motivates searches in the lower mass range. One such experiment is LDMX.

2.2 The Light Dark Matter eXperiment

2.2.1 Production of light dark matter

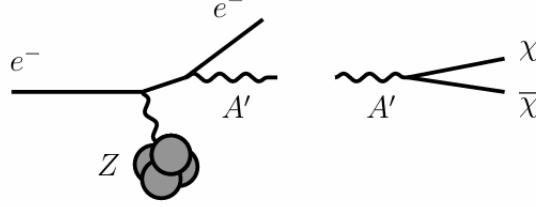
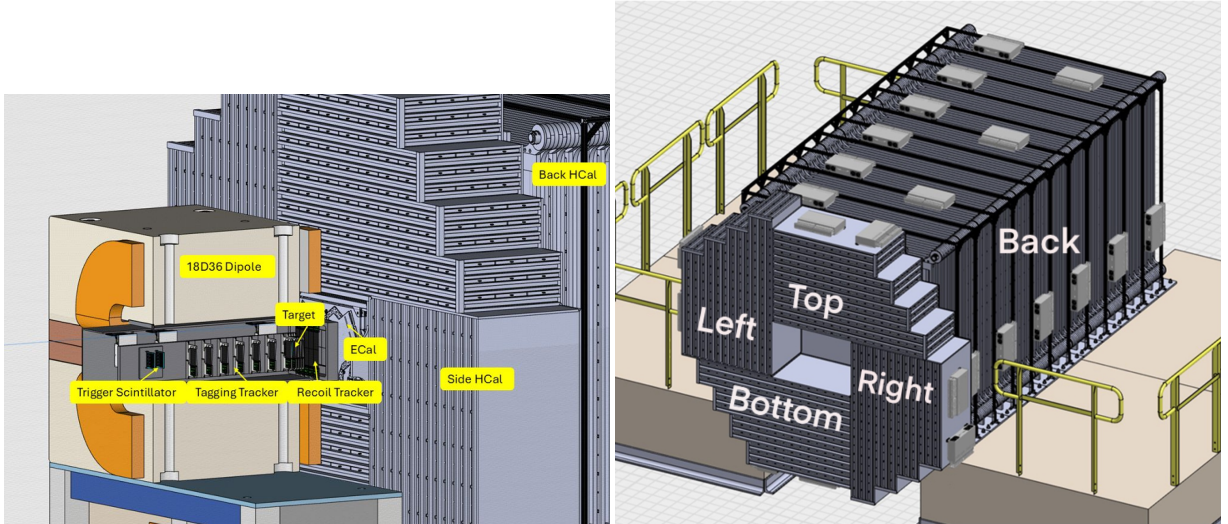


Figure 1: Production of dark matter through the theorized process dark bremsstrahlung: An electron interacts with a nucleus, produces a mediator which decays into a DM and anti DM-pair.

In the thermal relic freeze-out model, DM is required to have a small non-gravitational coupling to ordinary matter, which suggests that DM could be produced in accelerator-based experiments. In the case of light dark matter, the interaction between electrons and DM is essential for its thermal origin [3]. This coupling is what LDMX is designed to probe. DM is expected to be produced in a process called dark bremsstrahlung, which is shown in Figure 1. In this process, a high-energy electron interacts with a nucleus, resulting in the production of a DM mediator, also called a dark photon, which may subsequently decay into a pair of DM and anti-DM [2].

2.2.2 Experimental setup



(a) A close up of the LDMX detector.

(b) The HCal with its different sections labeled.

Figure 2: The LDMX detector. A trigger scintillator and a tagging tracker sit upstream of the target while a recoil tracker is located downstream of the target, all enclosed in a dipole magnet. An ECal is located behind the recoil tracker and is surrounded by a HCal [3].

LDMX will be carried out at SLAC and utilize the accelerator facility LCLS-II. Low-multiplicity electron bunches, provided from the Linac to end station A [3], will be directed

at a tungsten target. In the case of DM production, the electrons lose a significant amount of energy to the DM particles [2]. Therefore, the production of DM will be inferred from missing momentum. Hence, all particles entering and leaving the detector must be correctly identified, and their momentum must be precisely measured. The detector setup is shown in Figure 2. The first detector component that the electrons encounter is a Trigger scintillator, whose job is to inform the trigger about the number of electrons in the bunch [3]. The momentum and trajectory of the electrons are determined in a tagging tracker and a recoil tracker, both located inside a magnetic field to curve the path of the electrons. The tagging tracker is located upstream of the target to measure the incoming electrons, while the recoil tracker is positioned downstream of the target to measure the kinematics of the electrons after the collision. Behind the trackers an ECal is located to catch electromagnetic showers resulting from scattered electrons and bremsstrahlung photons. Additional background events such as muon conversion and neutral hadrons from photo-nuclear reactions are detected in the HCal [3].

2.2.3 The Hadronic Calorimeter

The HCal, shown separately in Figure 2b, consists of two main components: the side HCal, a semi-circular structure that surrounds the ECal, and the back HCal, a cuboid section located behind the ECal. The side HCal is divided into four additional sections: right, left, top and bottom. Each section of the HCal follows the same overall design with layers of steel absorber plates, whose purpose is to absorb the energy of the incoming particles, and scintillator bars, which convert the deposited energy into measurable signals. The scintillator bars are 20 mm thick, 50 mm wide and 2 m long in the back HCal, while they vary in length for the side HCal [3]. When particles travel through the scintillators, they produce light, which is read out by silicon photo-multipliers (SiPM's). The back HCal has one SiPM attached to each end of the bar and therefore has a double-ended readout, whereas the bars of the side HCal are equipped with only a single-ended readout due to structural constraints [3]. To optimize spatial resolution, the scintillator bars in successive layers are oriented in alternating directions. The orientations of the scintillator bars in the different sections are illustrated in Figure 3. The back HCal has scintillator bars oriented vertically and horizontally with their thickness oriented along the z -axis. In the side HCal, the orientation depends on the section: the left and right sections have the same orientation as the back HCal but rotated 90° around the y -axis, whereas the top and bottom sections can be viewed as the right and left sections rotated 90° around the z -axis.

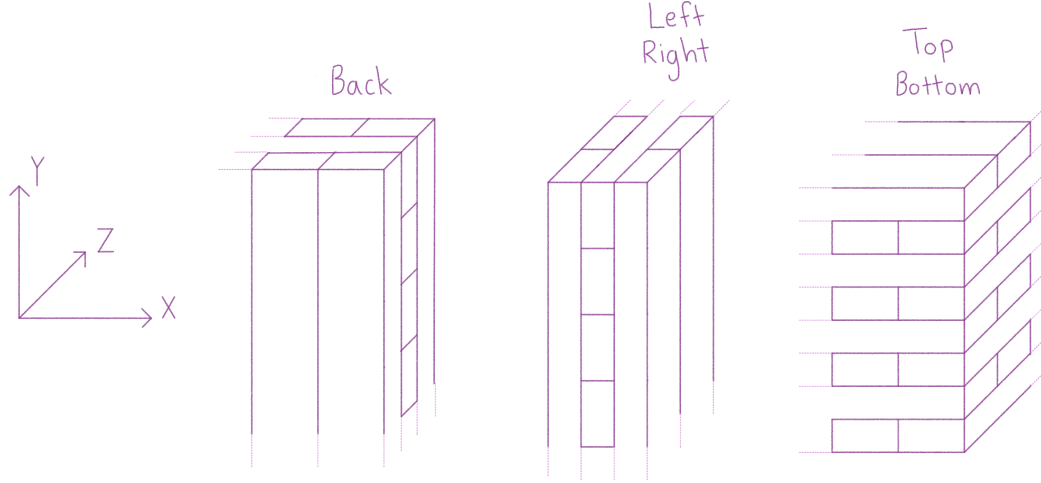


Figure 3: Scintillator orientations used for the different sections of the HCal. Note that the figure is not drawn to scale and that the absorber layers have not been included.

2.3 Cosmic muon measurements

2.3.1 Cosmic muons

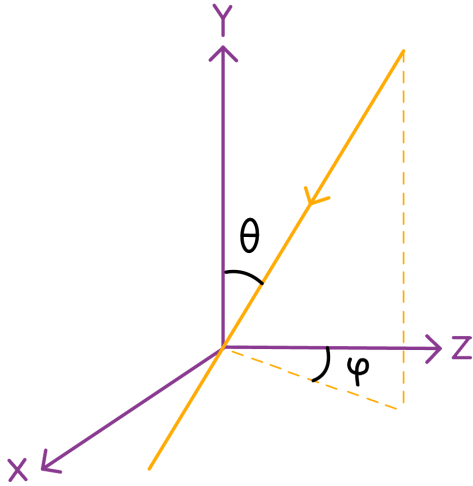


Figure 4: Polar angle (θ) and azimuthal angle (ϕ) of an incoming muon passing through the origin.

Muons are produced when cosmic rays interact with the atmosphere and continuously reach the surface of the Earth. Their incident direction can be described by two angles: the polar and azimuthal angle, shown in Figure 4. The azimuthal angle is defined around the y -axis and measured from the z -axis while the polar angle is measured from the y -axis. Cosmic muons are equally likely to arrive with any incident azimuthal angle, whereas the polar angle distribution is not uniform and instead smaller angles are more common. Figure 5 displays the cosmic muon flux at sea-level for the different polar angles $\theta = 0^\circ$ and $\theta = 75^\circ$.

At lower energies, smaller angles are favored, while angles around 75° are strongly suppressed. At energies above 100 GeV the flux becomes approximately independent of angle. In this project, muons are simulated between energies of 0-100 GeV, consequently, smaller angles should occur more frequently than larger angles.

Ionization loss occurs for charged particles when they interact with the electrons of matter and is the dominant source of energy loss for heavy particles at lower energies. A particle is considered minimally ionizing when its energy loss per unit distance traveled in a material reaches a minimum [7]. Figure 6 depicts the stopping power of a muon in copper. For muons, minimum ionization occurs at around 500 MeV, but unlike most particles, muons remain close to this minimum over a wide range of energies. Muons can therefore be considered MIPs in the approximate range of 100 MeV - 100 GeV.

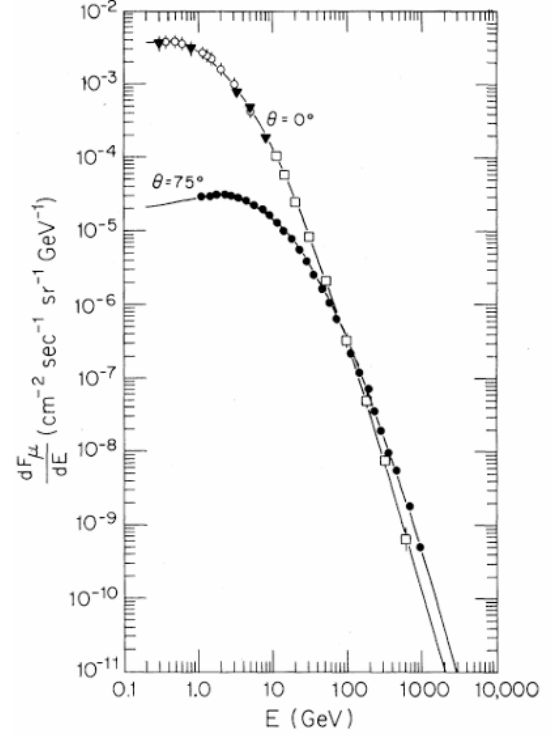


Figure 5: Cosmic muon flux at sea level for the different polar angles $\theta = 0^\circ$ and $\theta = 75^\circ$ [8].

A minimally ionizing muon (MIM) is predicted to deposit 0.233 MeV per mm traversed in the LDMX's scintillator material [9]. Therefore, muons should deposit 4.66 MeV when traveling through 20 mm of a scintillator bar.

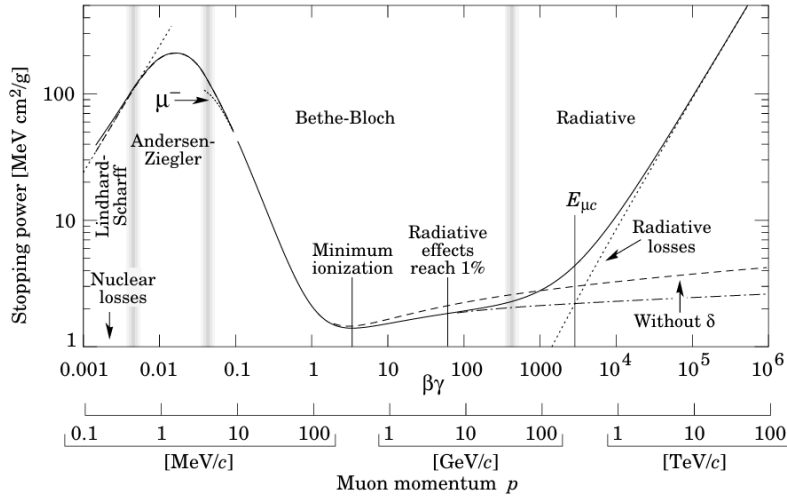
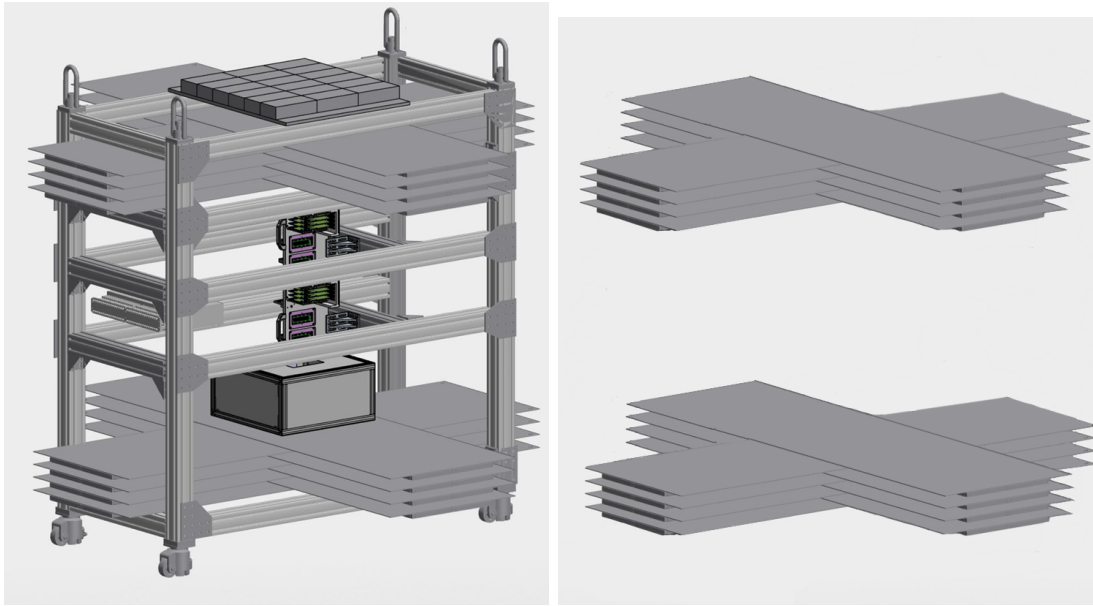


Figure 6: The Bethe-Bloch curve ($= \langle -dE/dx \rangle$) of a muon in copper. Muons are MIPs at the approximate range of 100 MeV-100 GeV [10].

2.3.2 HCal prototype



(a) Full prototype.

(b) HCal prototype.

Figure 7: The prototype that will measure cosmic muons at SLAC. The two cross like sections are the HCal, and other detector subsystems, such as a trigger scintillator and trackers, are located in-between [11].

Cosmic muons are very useful for physics experiments, as they occur naturally and are continuously available. This eliminates the need for accelerator-produced particle beams, thereby reducing energy consumption and cost as well as constraints such as limited beam time. In addition, due to their minimally ionizing behavior, the energy they deposit will follow an expected distribution. Hence, they are well suited for calibration and monitoring changes in the detector.

The prototype that will be set up at SLAC to measure cosmic muons is shown in Figure 7a. It consists of various detector subsystems. The central region contains components such as trigger scintillators, silicon trackers, and some modules of the ECal [11] [12]. The two cross like sections, separately shown in Figure 7b, are the HCal prototype, and are the focus of this project. One section is located at the top to measure the incoming muons, while the other is positioned at the bottom to detect the outgoing muons. Similarly to the top and bottom sections of the side HCal, the HCal prototype alternates between layers of scintillator bars oriented either along the x - or z -axis. The scintillator bars are read out at both ends [13]. Above the top section of the HCal prototype, a grid of lead bricks is located to filter out particles that are not muons.

3 Software

3.1 ldmx-sw

ldmx-sw is a simulation and reconstruction framework used by LDMX. The software provides a way to simulate events with Geant4 using different detectors and experimental setups [3]. Geant4 is a particle transport code that can simulate the trajectory and interactions of particles through detectors [14] [15]. It moves particles stepwise through

the detector, and at each step it simulates energy deposition, effects from magnetic and electric fields, and potential daughter particles. The code developed in this project can be found on GitHub [16].

The first step to generating cosmic muon simulation samples is to produce the particles themselves. This is carried out using an existing cosmic muon generator within ldmx-sw. The generator uses Monte Carlo techniques to generate cosmic muons based on their flux and the probability distributions of their energy and incident angle [8]. Section 4.4 explains this procedure in more detail. Information such as the position of the particles when entering the detector and their four-momentum is stored in a LHE file. To run the simulation, multiple parameters must be defined and gathered in a configuration file, which is then passed to Geant4. A configuration file, made by an earlier student, already exists for simulating cosmic muons through another detector and was used as a baseline for the project [9]. The results obtained from the simulation are given in a ROOT file. ROOT is a framework designed to store, process, and analyze data and is commonly used in physics experiments [17]. A ROOT file contains a so-called tree that is divided into branches. Each branch represents a specific set of data, such as information about the simulated particles. The branches are further divided into leaves that store the actual data obtained from the simulation.

3.2 Digitization and Reconstruction

Reconstruction is a process in which raw detector signals are converted into something more suitable for physics analysis [3]. In ldmx-sw, this procedure is applied not only to recorded detector data but also to simulated data. However, unlike real detector data, simulations already contain all information about the particles and their interactions and must therefore undergo an additional step before reconstruction called digitization. Digitization transforms the simulated data to mimic the electronic readout signals ¹ that would have been produced by the actual detector. After this, the data can undergo the same reconstruction process as the recorded detector data, which ultimately should yield a close representation of the originally simulated data. In ldmx-sw, the digitization and reconstruction of the simulated HCal interactions are performed by two processors called "HcalDigiProducer" and "HcalRecProducer". In order for these processors to perform calculations, such as light attenuation, they must be given information about the detector geometry. This is done in a file called hcal_geometry.py, which provides information such as the length of the scintillator bars.

The simulated data, which ldmx-sw receives directly from Geant4, are stored in two branches called "SimParticles" and "HcalSimHits". SimParticles contain information about the simulated particles, such as their momentum, charge, and particle ID. HcalSimHits stores information like the coordinates of an energy-depositing interaction and the corresponding energy deposition. These two branches contain truth-level information, which means that they provide true and exact information about the simulated particles and their interactions with the detector. The branch "HcalRecHits" holds the simulated data after it has undergone the digitization and reconstruction process. It contains information such as what section, layer, and scintillator bar was hit and how much energy was detected. Ideally, it should resemble the simulated data. In this project, most focus has been put onto investigating the reconstructed hits in the HCal prototype, but due to

¹i.e. pulses extended and sampled in time.

some unexpected results, the simulated hits have also been studied for comparison.

Because the reconstructed data give information about what section, layer, and bar was hit, it is easy to compare, for example, the number of hits in the different sections. If the same results is to be obtained from simulated hits, additional steps must be taken. Simulated hits hold information about at what coordinates an interaction occurred. Therefore, one has to manually check what section, layer and bar the coordinate corresponds to. In addition, multiple hits can be obtained within the same bar. In reconstructed data, this would correspond to only one hit, as the two energy deposits occur nearly simultaneously, resulting in the detector not being able to tell the individual signals apart. Therefore, if multiple energy deposits occur within the same bar in simulated hits, they are summed.

4 Implementation of a new detector geometry

4.1 GDML file

The main input Geant4 must be given is the generated particles, and information about the detector that they will pass through. The former is provided by the LHE file that is produced by the cosmic muon generator, and the latter by a so-called Geometry Description Markup Language (GDML) file. GDML files are based on the XML language and are used in physics experiments to describe detector geometries. A GDML file consists of the following five main blocks [18]:

- **Define:** The define block introduces constant variables that are used throughout the rest of the file to describe and put together different parts of the detector. For example, the dimensions of the scintillator bars and the number of layers. Positions that might be relevant are also defined, such as the position of the first layer.
- **Materials:** As the name suggests, the material section contains information about the composition of the materials used in the detector. It provides details about different isotopes that are used to describe various elements to ultimately define the material of the detector components.
- **Solids:** In the solid block, volumes are created by specifying a length, height, and width; or other relevant dimensions required to describe the shape of the object. In addition to the smallest building blocks of the detector, such as the scintillators, "mother volumes" must also be defined. These are larger volumes that are later used to contain the smaller "daughter volumes" [18]. The HCal region is, for example, the mother volume of the scintillators.
- **Structure:** It is in the structure block that the detector geometry is ultimately assembled. The detector volumes are assigned their respective material and the daughter volumes are assigned positions relative to each other inside the local coordinate system of their mother volume.
- **Setup:** The setup section defines the top volume of the geometrical hierarchy.

Ldmx-sw contains multiple GDML files that describe various detector versions. The main part of this project has been to construct a GDML file to describe the geometry of the HCal prototype.

4.2 Visualized geometry

Figure 8 shows the HCal prototype geometry which was defined in a GDML file. The images have been obtained from a Geant4 visualizer called OpenGL. The geometry includes two sections which are separated by a meter. Each section contains eight layers and can be seen in Figure 8a. The layers are further divided into 8 scintillator bars, most visible in Figure 8b. Each layer also includes a thin scintillator cover made of aluminum. The layers alternate between being positioned along the x - and z -axis. The layer located lowest in each section is directed along the z -axis and has been given layer number 1. The second layer, along the x -axis, consequently has layer number 2. Therefore, all layers pointing along the z -axis have odd numbers, while the layers along the x -axis have even numbers. The first scintillator bar in each layer has been given number 0. Section 4.3 explains in greater detail how these numbers are assigned. Figure 9 shows an example of the layer and bar numbering. The images are not drawn to scale for easier visualization. The origin of the coordinate system is defined as the center of the detector and midway between the two sections.

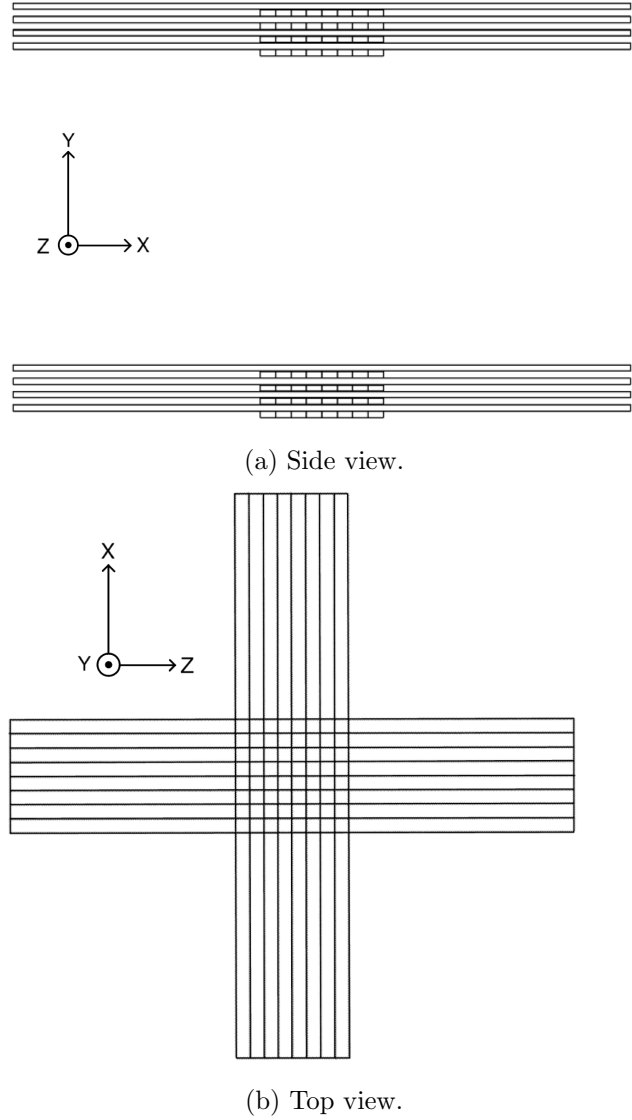


Figure 8: The HCal prototype geometry directly obtained from the GDML file viewed from two different angles.

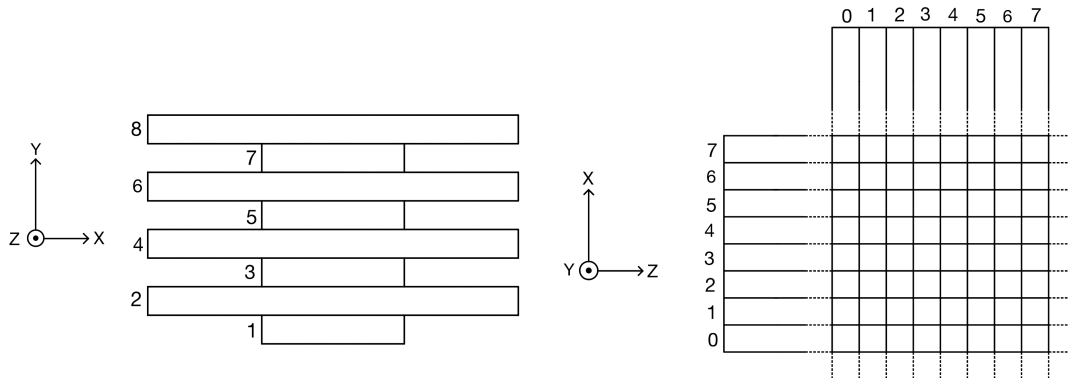


Figure 9: Numbers given to the layers and bars of the HCal prototype. The image is not drawn to scale.

4.3 Assigning copy-numbers

One of the main struggles to successfully simulate cosmic muons through the HCal prototype was to figure out how to correctly assign copy-numbers in the GDML file. Copy-numbers are unique numbers given to all physical volumes of the detector to distinguish between them. Copy-numbers are assigned automatically, starting from 0, but can also be set manually. In ldmx-sw, specific copy-numbers are given to the scintillator bars in the HCal to deduce valuable information from simulations; such as what section, layer, and scintillator bar was hit ². To be able to decode all this information from a single integer, ldmx-sw uses binary decoding. The copy-number given to each scintillator bar of the HCal geometry looks as follows:

$$\text{version} * 256^3 + \text{section} * 256^2 + \text{layer} * 256 + \text{bar}$$

The copy-number thus specifies what section and layer the scintillator belongs to, as well as its position within the layer by assigning it a bar number. There is an additional variable which defines the version of the copy-number scheme. There currently exist two copy-number schemes in ldmx-sw, versions 0 and 1. Version 0 does not include a way to specify individual scintillator bars [13], and therefore version 1 was used for this project.

As mentioned, the HCal that will be used for the actual experiment to search for DM consists of five different sections. Each section has been given a specific number in ldmx-sw, presented in the table below.

Section	Assigned number
Back	0
Top	1
Bottom	2
Right	3
Left	4

Table 1: The number assigned to each section of the HCal in ldmx-sw.

For example, the 8th scintillator bar, in the third layer of the bottom section, is given the following copy-number:

$$1 * 256^3 + 2 * 256^2 + 3 * 256 + 7$$

The different sections have different geometry requirements that must be met. For example, the back HCal must have scintillator bars oriented either horizontally or vertically, while the top and bottom sections must have scintillator bars oriented along the x - or z -axis. If a scintillator bar is given section number 0 in the GDML file but found to be oriented along the z -axis, ldmx-sw will raise an error. Since the sections of the HCal prototype have the same scintillator orientation as the top and bottom sections of the side HCal, they were assigned the section numbers 1 and 2 and therefore assumed to be parts of the side HCal.

²This is similar to unique channel numbers in a real detector.

4.4 Missing muons

The first results obtained when simulating cosmic muons through the HCal prototype showed discrepancies between the number of hits in the different layers and sections. Layers with scintillator bars oriented along the x -axis were hit more frequently than those with bars along the z -axis. In addition, the bottom section showed approximately 25% less hits than the top section. Upon investigation, the issue was found to originate from an error in the cosmic muon generator script rather than in the new detector geometry. The generation of cosmic muons proceeds as follows:

The generator starts by producing a muon with some energy and angle, randomly sampled from a known distribution. The momentum of the muon is calculated and it is given a random position inside the detector volume. Using a line-parametrization, determined from the momentum, it is found whether the muon intersected the top of the detector or not. If it did, this point is assigned as being the vertex of the muon, and if it did not, the other sides are checked in the same manner. This is illustrated in Figure 10. Due to an error in the code, initially only intersections with the sides in the x -plane were checked, and if the muon did not intersect, it was never assigned a vertex. Therefore, muons that only intersected through the z -plane were not simulated. This caused a suppression of hits in the layers oriented along the z -axis and the bottom section.

In the generator, the detector volume is simplified by a boundary box, specified by the minimum and maximum dimensions of the detector volume, which can be seen in Figure 10. Since the HCal prototype is not a definite box, some generated muons will never intersect the detector. This does not affect the results but leads to simulation of muons that do not contribute to any useful data. Due to time limitation, it was decided not to put any effort into defining a more precise detector volume in the generator.

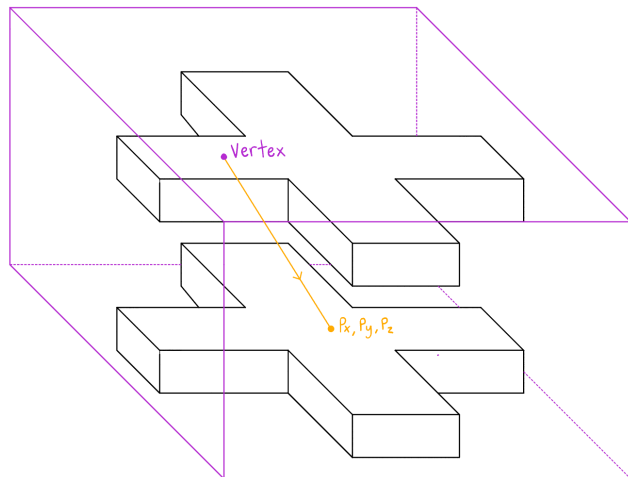


Figure 10: The HCal prototype and the boundary box which is used to define the detector volume in the cosmic muon generator. A muon is given a vertex where it first intersected the boundary box.

It was observed that if the boundary box was given the exact same coordinates as the maximum and minimum dimensions of the HCal prototype, the resulting ROOT-file showed some muon vertices inside the detector volume. This caused a noticeable reduction of hits in the uppermost layer of the top section. The boundary box was increased by 50 mm in all directions, which resolved the issue.

5 Result and analysis

5.1 Hits in layers and sections

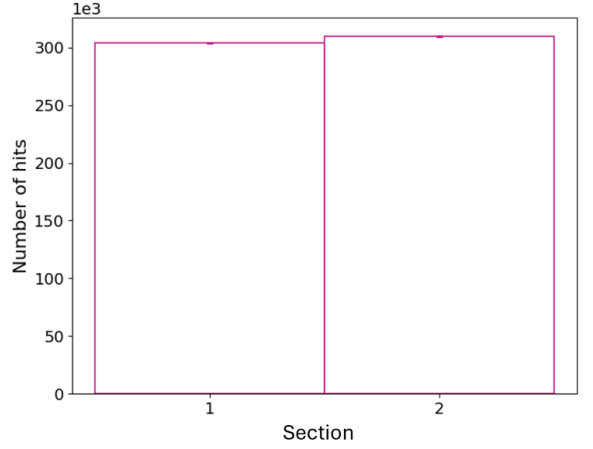
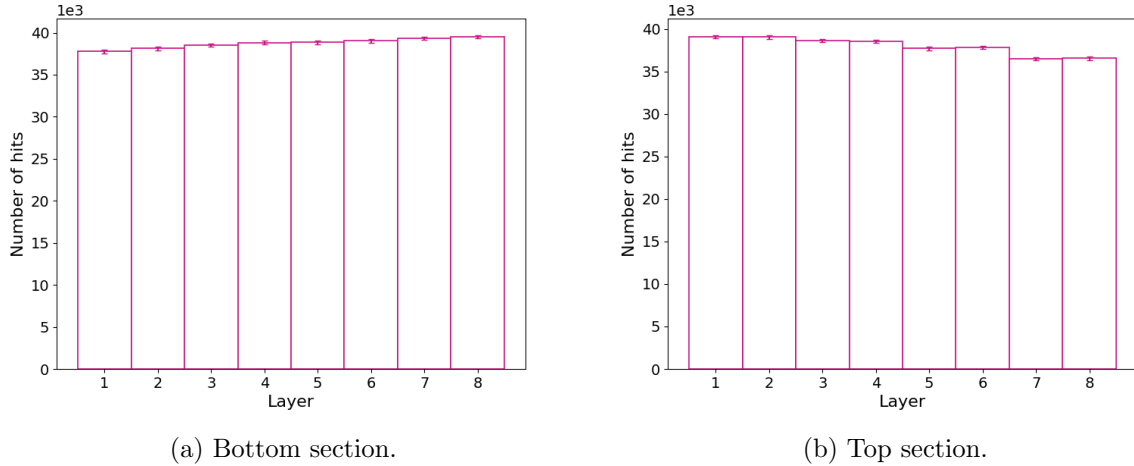


Figure 11: Number of hits in the different sections when simulating cosmic muons through the HCal prototype. 1 equals the top section and 2 equals the bottom section.



(a) Bottom section.

(b) Top section.

Figure 12: Number of hits in the different layers when simulating cosmic muons through the HCal prototype.

Figure 11 shows the number of hits in the top (1) and bottom (2) sections, and Figure 12 shows the number of hits in the different layers in the two sections. Error bars are included in each bin and represent their statistical uncertainty, estimated from the square root of the counts. Because the azimuthal angle distribution of cosmic muons are uniform, it was expected that the simulation would yield an approximate equal number of hits in both sections and all layers. However, this is not observed. Instead, the bottom section receives more hits than the top section. The difference between the number of hits in the different sections is not substantial, but the small uncertainties suggest that simulating more events would likely yield a similar result. There is a very clear difference between the number of hits in the different layers. The different sections follow opposite trends: The top section has the least hits in layer 8 (the top layer) and the most in layer 1 (the bottom layer), while the bottom section has the most hits in layer 8 and the least in layer 1.

To further investigate these results, muons were generated with a particle gun instead

of the cosmic muon generator. With a particle gun, the initial position, direction, and energy of the muons can be specified, allowing for more precise testing and understanding of their trajectory and interactions.

At first, positive muons with energies of 10 GeV were generated from the coordinates $(x, y, z) = (0, 722, 0)$ and directed along the negative y -axis. The x - and z -coordinates were chosen such that the muons would intersect the center of the detector, while the y -coordinate ensured that the muons are generated 50 mm above the top layer, consistent with what was done in the cosmic muon generator. This turned out to yield an even stranger result, with a significant difference between the number of hits in layers along the x - and z -axis, which can be seen in figure 23 in the appendix. The observed results are likely caused by edge effects, as the boundary between two scintillators is located in the center of the detector. This effect was eliminated by increasing the x - and z - coordinates by 25 mm, which ensured the muons would intersect the middle of a scintillator.

It was expected that using the particle gun would yield one of two outcomes:

- An equal number of hits in both sections and layers, which would indicate that the cause of the discrepancies lies in the cosmic muon generator.
- Show the same results, which would mean that they instead arise from a physical process or inaccuracies in the GDML file or the reconstruction process.

The outcome is shown in the figures below.

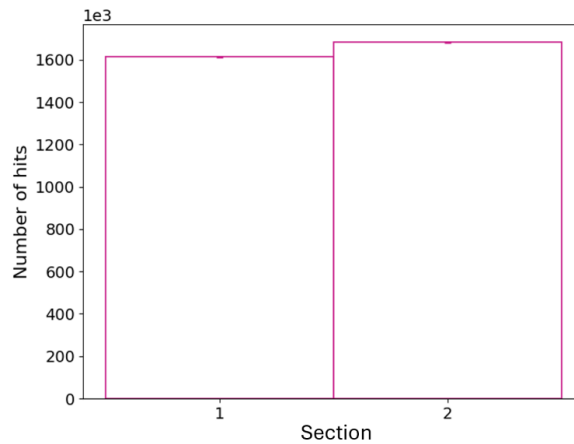
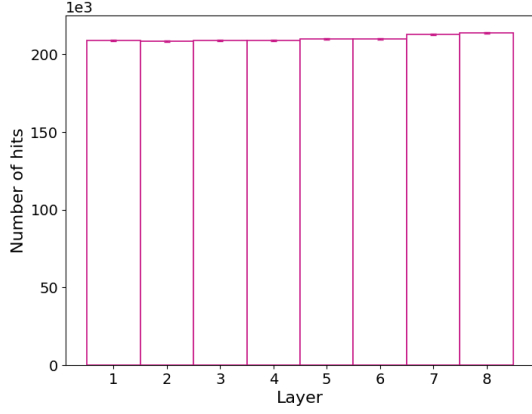
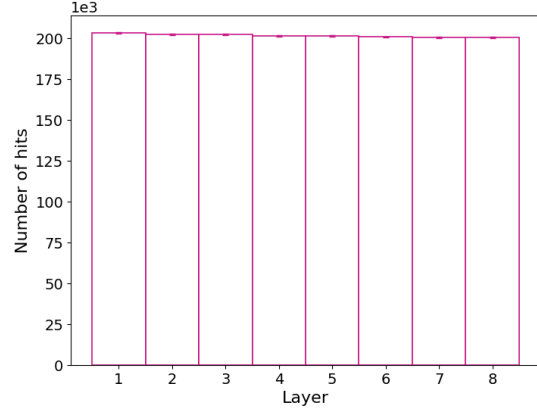


Figure 13: Number of hits in the different sections when directing muons down through the detector with a particle gun.



(a) Bottom section.



(b) Top section.

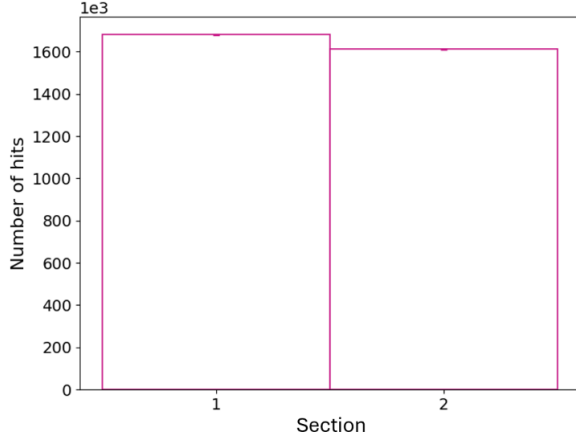
Figure 14: Number of hits in the different layers when directing muons down through the detector with a particle gun.

When using the particle gun, the excess number of hits in the bottom section becomes more apparent. This means that the discrepancy seen in Figure 11 likely has an underlying cause. In addition, the number of hits in each layer in the different sections follows the same trends, although not as noticeable. This concludes that the observations are not caused by the cosmic muon generator.

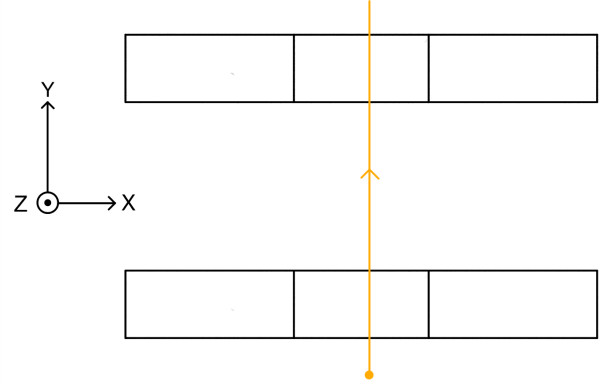
To try to determine whether the asymmetry between the number of hits in the different sections and layers originates from a physical process, the muons were generated from two additional positions: 50 mm below the bottom section, directed up through the detector, as illustrated in Figure 15b, and 50 mm above the bottom section, directed downward, as shown in Figure 16b. If the asymmetries are caused by a misinterpretation of the detector geometry somewhere in the software, the results should not change. If instead they are caused by a physical effect, the hit patterns should depend on where the muons are generated and on their direction of propagation, and the following should be observed:

- Muons entering from below should now produce more hits in the top section compared to the bottom section.
- Generating muons right above the bottom section should make it behave as the top section, meaning it should receive the most hits in layer 1 and the least in layer 8.

The results are presented below, with figure 15a showing the number of hits per section when muons are directed up through the detector, and figure 16a showing the hit distribution in the bottom section when muons are generated 50 mm above it.

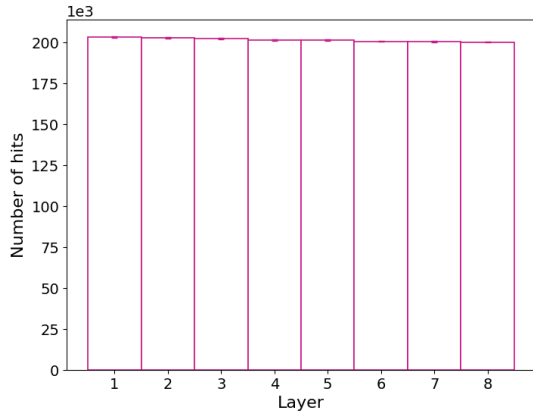


(a) Number of hits per section.

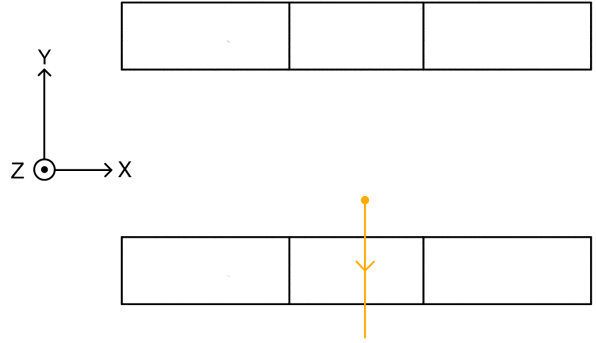


(b) Illustration of the trajectory of the muons.

Figure 15: Number of hits per section when shooting muons from the bottom, up through the detector and an illustration of the muon trajectory.



(a) Number of hits per layer.



(b) Illustration of the trajectory of the muon.

Figure 16: Number of hits in the different layers of the bottom section when generating muons 50 mm above it and an illustration of the path of the muons.

These results seem to indicate a physical process, as the hits per section now show the opposite result, as well as the bottom section receiving approximately the same number of hits per layer as the top section did in the previous simulation.

From this it can be concluded that the number of hits does not depend on whether it is the top or the bottom section or layer, but rather on where it is located with respect to the incoming particles. More specifically, the following is observed:

- The last section obtains the most hits.
- The first section obtains the least hits in the first layer and the most hits in the last layer.
- The last section obtains the most hits in the first layer and the least in the last layer.

The observed trends seem to suggest that: as the muons pass through the first section, secondary particles are produced and escape into the next layers, which results in more hits. In the space between the sections, secondary particles continue to be produced, since more hits are observed in the first layer of the last section, than the last layer of the

first section. This could be reasonable since the space surrounding the HCal prototype is filled with air which could be ionized by the traversing muons. However, creation of secondary particles in the first section implies that a similar process should occur in the last section. Instead, the number of hits decreases in the later layers, contradicting this theory. A possible explanation would be that the muons start to decay or stop in the last section.

In hopes of more insight, the branch `SimParticles`, which contains the creation and end coordinates of simulated particles, was studied. Surprisingly, not a single particle was found to have been created or decayed within the detector volume or the space between the sections. Instead, another phenomenon was discovered: multiple electrons are created and decay in the air surrounding detector. According to the ROOT-file, most of these electrons are created from ionization. When using the particle gun, the muons only traverse the middle of the detector and should not cause any ionization of the air around it. A deeper analysis of how these electrons are brought into existence has not been conducted due to time limitations.

There is a possibility that the observed trends are caused by secondary particles even though `SimParticles` does not store their information. It could be that `ldmx-sw` does not keep the data of secondary particles created within the calorimeter region to save space [12]. This would explain why secondary particles are only observed outside the detector region. Further investigation is needed to determine whether the irregular hit distributions are caused by secondary particles or errors in the code.

5.2 Deposited energy in scintillator bars

One of the main goals of this project was to analyze the reconstructed energy depositions in each scintillator bar of the HCal prototype to ensure that the geometry behaved correctly and that every bar was hit when incorporated into `ldmx-sw`. The energy deposition in each scintillator bar followed a Gaussian-Landau convolution distribution, which is the expected distribution for the energy loss of a particle traveling through some material. There was no single bar that stuck out compared to the others. However, a very unexpected result was observed when comparing the detected energy in scintillator bars in the different layers. Figure 17 shows the detected energy distribution in all bars along the x -axis and z -axis in the top section. A Gaussian-Landau convolution has been fit to the data.

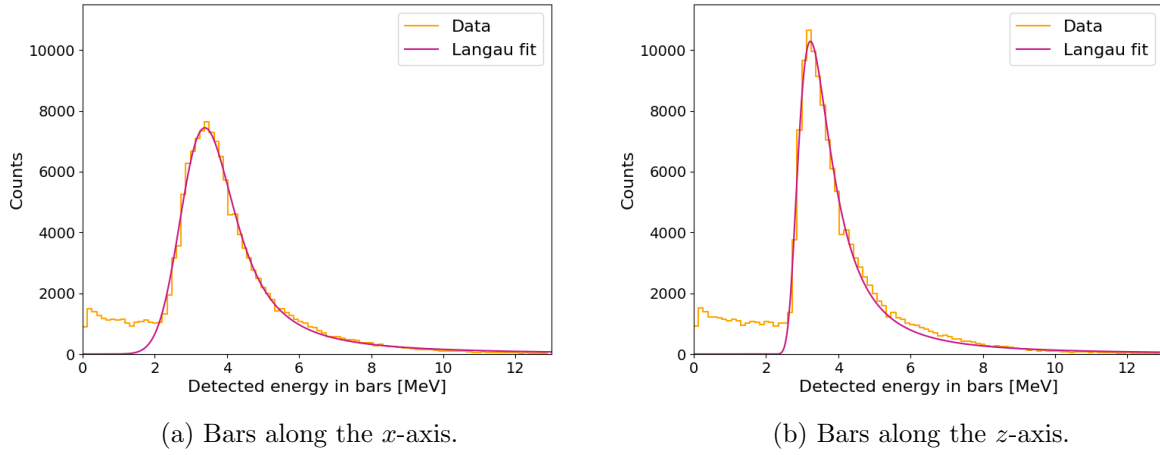


Figure 17: The detected energy (orange) in scintillator bars of different orientations in the top section obtained after digitization and reconstruction of the simulated data. "Langau" refers to Gaussian-Landau convolution (purple).

The detected energy is expected to be nearly identical across all bars, independent of orientation, but the width and height of the distribution varies significantly depending on whether the bars are oriented along the x - or z -axis. Bars along the x -axis are observed to have a broader distribution in addition to a smaller peak height, while the opposite holds for bars along the z -axis.

Similar results are obtained for the bottom section, although not identical. Table 2 compares the most probable value (MPV), amplitude, and uncertainties obtained from the Gaussian-Landau convolution fit to the detected energy distributions in bars along the x - and z -axis in both the top and bottom sections.

Section	Top		Bottom	
Bar orientation	along x	along z	along x	along z
MPV (MeV)	3.38 ± 0.010	3.23 ± 0.008	3.63 ± 0.013	3.60 ± 0.014
Amplitude (counts)	7469 ± 85	10289 ± 115	7208 ± 96	9345 ± 136

Table 2: The most probable values, amplitudes, and uncertainties obtained from the Landau-Gaussian convolution that was fitted to the detected energy distribution obtained from the reconstructed data.

Both sections have noticeable differences in amplitude depending on the bar orientation. The top section has a MPV of approximately 3.3 MeV while the bottom section has a MVP around 3.6 MeV. This indicates that the distribution is shifted toward lower energies for the top section.

To investigate where these issues could originate from, the simulated hits were studied as well. Encouragingly, the anomaly did not persist. The deposited energy distributions in bars along the x - and z -axis, in the top section, obtained from the simulated hits, are shown in Figure 18. The values obtained from the Landau-Gaussian convolution are presented in Table 3.

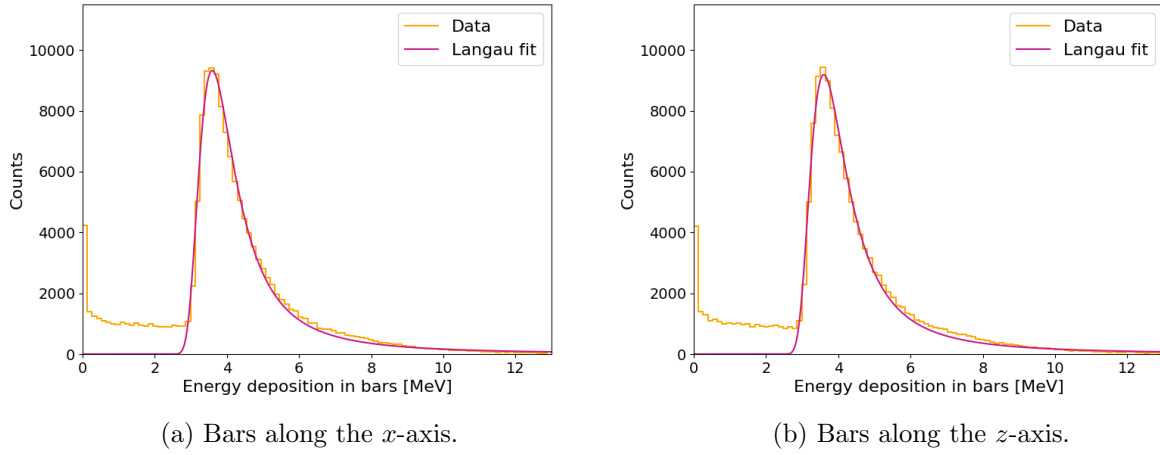


Figure 18: The deposited energy in scintillator bars of different orientations in the top section obtained from simulated hits. A Landau-Gaussian convolution has been fitted to the data.

Section	Top		Bottom	
Bar orientation	along x	along z	along x	along z
MPV [MeV]	3.59 ± 0.007	3.60 ± 0.012	3.59 ± 0.007	3.60 ± 0.010
Amplitude [Counts]	9329 ± 101	9193 ± 95	9372 ± 99	9248 ± 110

Table 3: The most probable value, amplitude and uncertainties obtained from the Landau-Gaussian convolution fit to the energy deposition obtained directly from simulation.

The distributions are nearly identical. Both sections have a MPV around 3.60 MeV and an amplitude of approximately 9300, independent of bar orientation. These values are most similar to those obtained for bars oriented along the z -axis in the bottom section after reconstruction of the simulated data. These results indicate that the discrepancies seen in Figure 17 and presented in Table 2 originate from the digitization or reconstruction process.

To verify this, HcalDigiProducer and HcalRecProducer were replaced by another processor called "HcalSimpleDigiAndRecProducer". This processor does not pass the data through digitization; instead, it performs a very simple reconstruction directly from the simulated data. The results are presented in Figure 19 and Table 4.

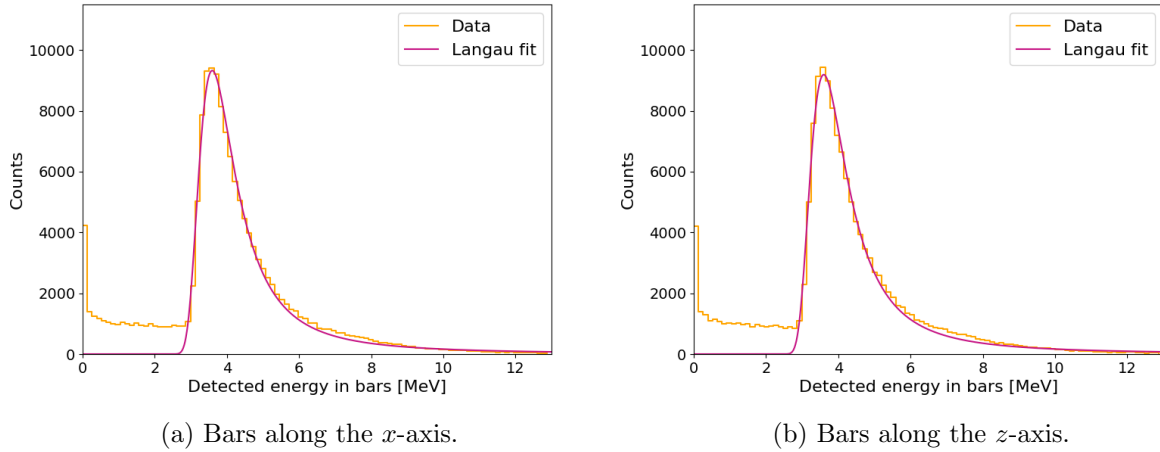


Figure 19: The detected energy in scintillator bars of different orientations in the top section obtained after a simple reconstruction of the simulated data.

Section	Top		Bottom	
Bar orientation	along x	along z	along x	along z
MPV [MeV]	3.59 ± 0.012	3.60 ± 0.011	3.59 ± 0.011	3.60 ± 0.013
Amplitude [Counts]	9329 ± 101	9194 ± 95	9372 ± 99	9249 ± 108

Table 4: The most probable value, amplitude and uncertainties obtained from the Landau-Gaussian convolution fit to the simulated data after a simple reconstruction.

These results show almost perfect agreement with the simulated data, concluding that there is a problem occurring in the digitization or reconstruction process.

Due to time limitation, the exact cause of the failing reconstruction has not been determined, but there are multiple possible explanations. The most probable cause for the anomalies is the underlying assumption that the sections of the HCal prototype are the top and bottom sections of the side HCal. There is a high probability that this causes the software to perform computations specifically designed for the geometry of the side HCal.

The side HCal has a more complex geometry than the HCal prototype, with varying scintillator bar length depending on both layer and orientation. In particular, the lengths of the bars oriented along the z -axis are much shorter than those oriented along the x -axis. This significant difference between scintillators of distinct orientation leads to a natural suspicion that it might be related to the different energy distributions obtained for bars along the x - and z -axis. Although the lengths of the scintillator bars of the HCal prototype have been defined in the file `hcal_geomey.py`, which provides information about the detector geometry to `ldmx-sw`, there might be hard-coding of bar lengths elsewhere in the software.

Another noteworthy difference between the side HCal and the HCal prototype is that the top and bottom sections of the side HCal are mirrored and inverted with respect to one-another, while for the HCal prototype, they are identical, just positionally shifted in the y -axis. In addition, the side HCal expects an ECal to be positioned between the sections. This might explain why the detected energy distributions obtained from the two

sections of the HCal prototype had different MPVs. An additional factor that could be causing an incorrect digitization and reconstruction of the simulated data is that, unlike the side HCal, the HCal prototype has a double-ended readout.

In order to verify or deny these possibilities, further investigation and understanding of how the HCal geometry is interpreted and used in ldmx-sw is required. Because of the unusual results acquired when using HcalDigiproducer and HcalRecProducer; HcalSimpleDigiAndRecProducer was used for the rest of the analysis.

5.3 Detected energy vs polar angle

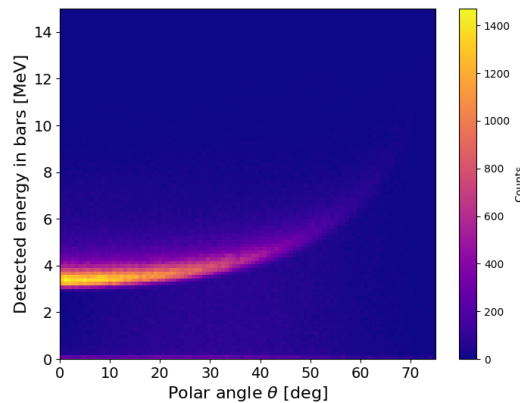


Figure 20: Detected energy in bars vs polar angle.

Figure 20 shows the detected energy in the scintillator bars with respect to the polar angle of the incoming muons. Most cosmic muons that enter the HCal prototype will have small polar angles and therefore travel through approximately 20 mm of material in each scintillator bar, which should result in an energy deposition of 4.66 MeV. As the angle increases, the muons pass through more material, causing them to deposit more energy per scintillator bar. As expected, there is a MIM-band that increases approximately proportional to θ^2 . However, at small polar angles, the muons do not deposit 4.66 MeV, but instead around 3.6 MeV, as presented in Table 4. Thus, the MIM-band is located lower than theory suggests. Instead of depositing 0.233 MeV/mm, the muons deposit only 0.180 MeV/mm. This result is similar to observations made by an earlier student who studied cosmic muon interactions with the HCal. In this study, the observed energy deposition was 0.170 MeV/mm [9]. A possible explanation to the energy discrepancy was that daughter particles decayed and deposited some energy in the absorber layers. Observing similar results in a detector that does not include absorber layers may point to the exclusion of this idea. Instead, as also suggested by the other student, the energy the muons deposit in the scintillator bars might be lower than previously thought.

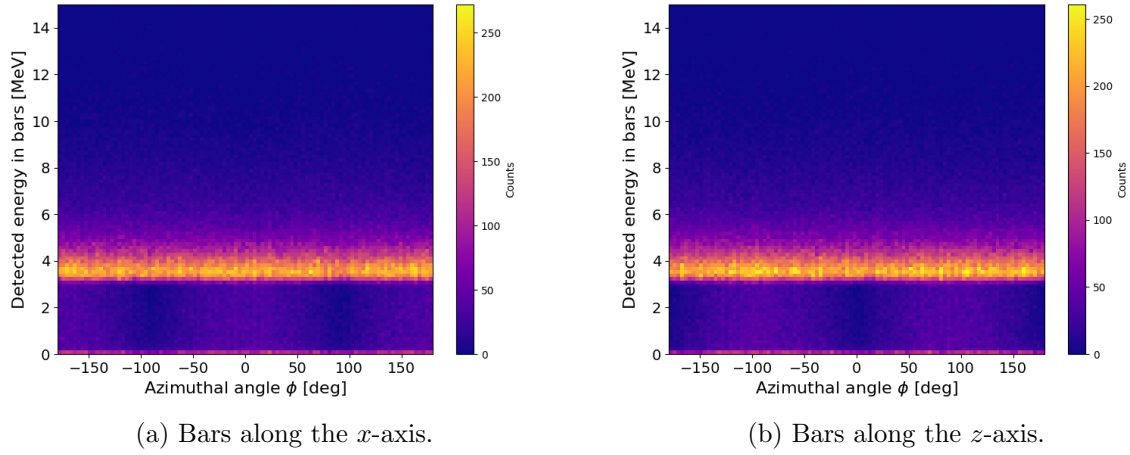
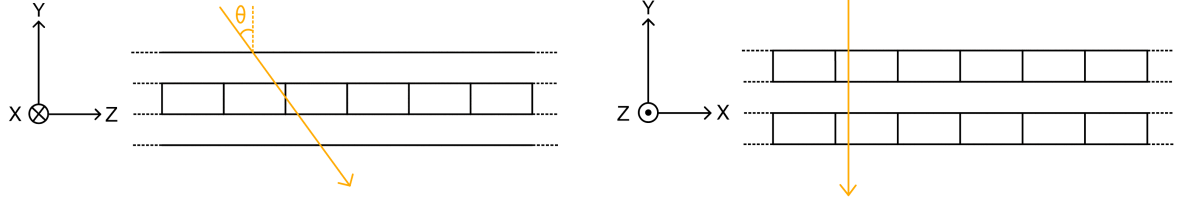


Figure 21: Detected energy in bars vs azimuthal angle.

The energy detected in the scintillator bars for different azimuthal angles is shown in Figure 21. Both bars along the x -axis and the z -axis display a continuous bright MIM-band at 3.6 MeV. This band corresponds to smaller polar angles, for which the azimuthal angle does not contribute to a noticeable difference in energy deposition. There is a noticeable smearing of the band toward higher energies, which corresponds to larger polar angles.

Initially, it was speculated that an increase of higher energy depositions would be observed at $\phi = \pm 90^\circ$ for bars along the x -axis and at $\phi = 0^\circ$ and $\phi = \pm 180^\circ$ for bars along the z -axis. At these angles, the muon traverses the length of the scintillator bars. Therefore, at large polar angles the muon could travel rather far in the same scintillator bar, depositing a lot of energy. However, this is not observed, which is most likely because large polar angles are more rare.

Instead, another pattern is observed at the mentioned angles: an absence of low energy depositions. A possible explanation for this is that; when a muon travels along the length of scintillator bar, it nearly always passes through 20 mm of material or more per bar. For example, if a muon enters the detector with some polar angle θ and azimuthal angle $\phi = 0^\circ$, as illustrated in Figure 22, it travels along the length of the bars oriented along the z -axis. There is a rather high possibility that the muon will pass through more than one scintillator per layer, in layers oriented along the x -axis, as shown in Figure 22a. Hence, the muon will traverse less than 20 mm of scintillator material per bar; which results in energy deposits under the MIM-band. Meanwhile, the muon will only intersect one bar per layer, in layers along the z -axis, as illustrated in Figure 22b. This means that the muon will nearly always travel through 20 mm of scintillator material or more, with the very few exceptions where the muon reaches the end of the bar before fully passing through it. Therefore, only very few energy depositions are observed below the MIM-band for bars along the z -axis at $\phi = 0^\circ$.



(a) A muon intersecting two bars in the same layer along the x -axis. (b) A muon intersecting one bar per layer along the z -axis.

Figure 22: An example of the trajectory of a muon entering with some polar angle θ and azimuthal angle $\phi = 0^\circ$ viewed from two different directions.

6 Conclusion and outlook

The main part of this project has been to write a geometry description for the HCal prototype that will be assembled at SLAC to detect cosmic muons. The HCal prototype geometry has been specified in the cosmic muon generator, a GDML file, and a Python file which supply information to ldmx-sw.

The hit distributions in the different sections and their layers follow some unexpected patterns. Simulating cosmic muons through the HCal prototype results in an increase of hits in layers further down in the top section, while the bottom section instead has a decrease of hits in later layers. In addition, the bottom section receives more hits in total. This phenomenon persists when the cosmic muon generator is replaced with a particle gun. The results indicate a physical effect such as the creation and decay of secondary particles. A deeper analysis should be conducted to verify whether the creation of secondary particles is the cause of the irregular hit distribution or if it is caused by errors in the code.

The distribution of the detected energy in scintillator bars obtained after digitization and reconstruction of the simulated data differs considerably depending on whether the bars are oriented along the x - or z -axis. The discrepancies do not persist when studying the simulated hits, which points to a problem occurring in the digitization or reconstruction process. This is further confirmed by observing reasonable results when using a processor that performs only a simple reconstruction.

These results are probably caused by the assumption that the HCal prototype is the top and bottom sections of the side HCal. Calculations, or variables, specifically designed for the side HCal are likely applied somewhere in the software, leading to faulty results. Further investigation of the digitization and reconstruction process is required to draw a definite conclusion about the origin of the discrepancies. Most likely, additional changes must be made to the software.

The energy deposited in the scintillator bars is lower than estimated and aligns with the results obtained in an earlier study of the HCal. This indicates that the muons might deposit less energy in the scintillator material than initially estimated.

Due to a lot of hard-coding in ldmx-sw, successfully including a new detector that does not resemble the expected geometry of the normal detector layout proved to be more difficult than anticipated. A considerable amount of time was dedicated to understanding

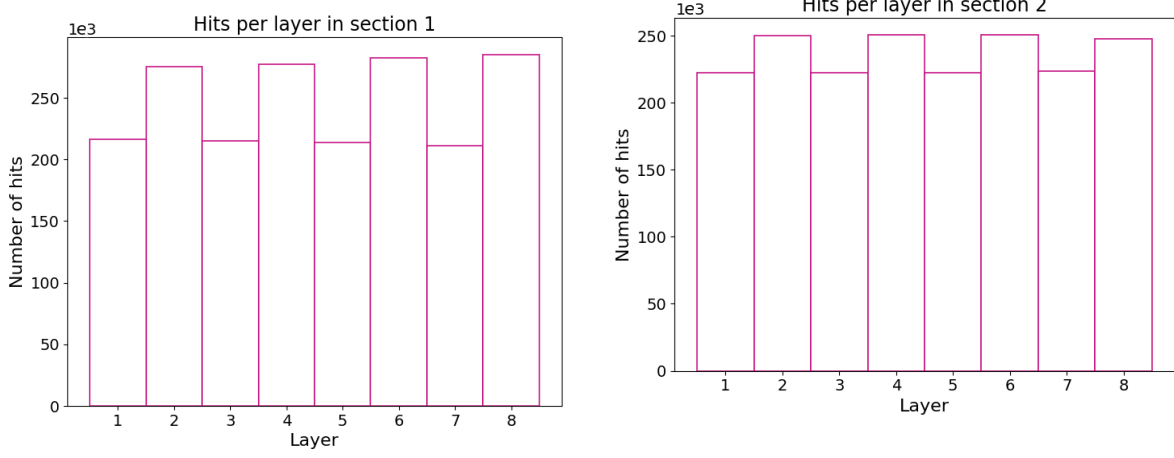
and searching for answers in various files of the software. A detailed documentation of how detector geometries are implemented into, and interpreted by, the software would have been very useful and might be something that should be considered in case of future implementations of new detector geometries.

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7 Appendix

Figure 23 presents the hit distribution in the different layers in the different sections when generating muons from the coordinates $(x, y, z) = (0, 722, 0)$ down through the detector with a particle gun.



(a) Top section.

(b) Bottom section.

Figure 23: Number of hits in the different layers in the top and bottom section when directing muons through the center of the detector with a particle gun.