Simulation of Particle Detectors with Geant4

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MSc. In Advanced Physics - Particle Physics

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Abstract

In this experimental report results of two different applications developed using the Geant4 simulation toolkit are presented. The main goal of this project is to test the validity of the designed simulation by comparing its output with the public results from Meroli's publication. For this purpose, we have developed an electromagnetic shower simulation of particles traversing a 5.6 μm thick silicon layer. The second part of this work has the purpose of exploring the options that Geant4 offers for particle detector simulation, and thus a simulation of the CMS calorimeter system (ECAL + HCAL) has been implemented.

Contents

1 Introduction

Nowadays, the theoretical framework over which the particle physics field lies is the **Standard Model** (SM). Even though the SM has proved to be the most accurate theoretical model the physics community has worked with, it is unlikely that it condenses the final fundamental aspects of nature. The main approach for finding physics that go beyond the SM fundamentals at the **high energy frontier** (which is the regime in which we are interested in), the use of high-end particle accelerators is required, as we need to produce particles with great energies in order to search for these new physics.

However, since most particles interact at some level with the materials that build a particle detector, a solid knowledge on how these particles interact with matter is required. Thus, the GEANT4 [1] developers offer a simulation toolkit that provides with the necessary tools for the simulation of particle interactions with different materials that can be used to build particle detectors.

In the following sections, two different simulations are presented: one of them has the purpose of reproducing the results that were published by S. Meroli, D. Passeri and L. Servoli [2] in 2011. In this publication, the deposited energy of 100 MeV electrons and 12 GeV protons traversing a silicon detector is measured. The second simulation is presented as an extra exercise that aims to explore further in the offered options of the GEANT4 package, and for that we have designed a simulation of the CMS calorimeter system (ECAL and HCAL) [3]. The implementation of both results can be found in reference [4].

2 Simulation of a silicon layer

As commented during the introduction, the main goal of this work is to compare the obtained results with a self-implemented simulation of a 5.6 microns silicon layer in which electrons deposit their energy, as a consequence of its interaction with silicon atoms and nuclei.

As for the technical implementation using GEANT4, the thickness of the detector was set to be 5.6 μm, and thus the built target was designed to be an squared box with each lateral being half the total thickness of the detector. The generated primaries consisted on just one electron with an initial energy of 100 MeV (reproducing those of Meroli's) that was carefully placed outside the target and propagated through the detector linearly in the X axis. **Fig.** 1 shows an overview of both the world and the detector used for this simulation.

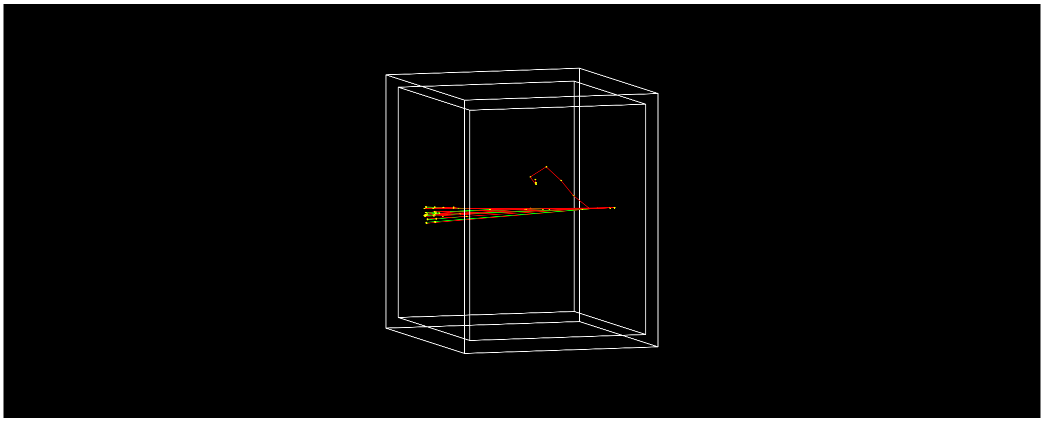


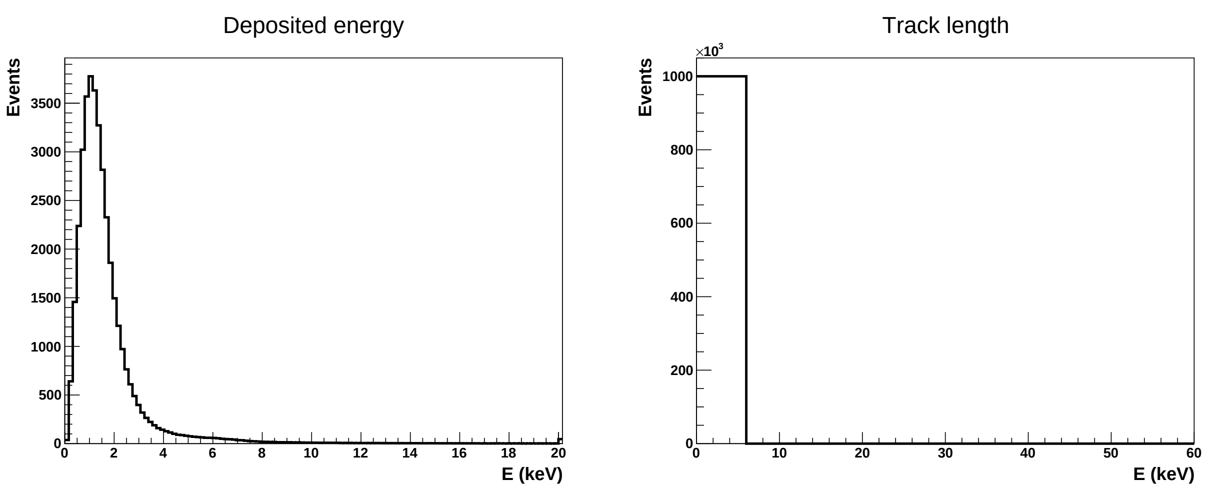
Figure 1: An image showing the dimensions and the shape for the detector used in the comparison with Meroli's experiment. The image shows the passage of ten electrons with an energy of 100 MeV.

The simulation run over one million of events, recording the deposited energy of the electron along the detector and the length of its track. The results on both the energy deposition distribution and total length of track can be found in **Figs.** 2a and 2b respectively. The distribution shape for the deposited energy shows a peak with center in the most probable deposited energy by the electromagnetic shower generated in the material. Since the electrons that enter the silicon target have enough energy not to be stopped by the target, the track length distribution is just one bin with one million entries, showing that all electrons are able to fully get through the target.

The deposited energy distribution is correctly modeled as shown in **eq.** 1 [2],

$$f(x,\Delta) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} f_L(x, \Delta - \tau) e^{-\frac{\tau^2}{2\delta_2}} d\tau \tag{1}$$

where $f(x,\Delta)$ is known as the "stragglin function". This result shows that the energy distribution for a fast charged particle traversing a certain amount of material can be modelled as the convolution of a landau and a normal distribution with variance δ_2.



(a) (b)

Figure 2: Distribution of deposited energy (a) and total length of the electromagnetic shower (b) after the interaction of 100 MeV electrons that travel along the silicon target.

In order to fully compare the validity of the simulation, a set of experimental data points from the original publication was available. The first thing one needs to do is to normalize the output of the simulation to the integral of the experimental points, since in this case the simulation contains much more statistics than the experimental data sample. Once the distributions have been normalized, a fit [5] to the experimental data is performed and also compared with the simulation. The result is shown in **Fig.** 3, where the experimental data and the simulation, along with two different fits can be found. A summary of the fit parameters can be found in **Table** 1.

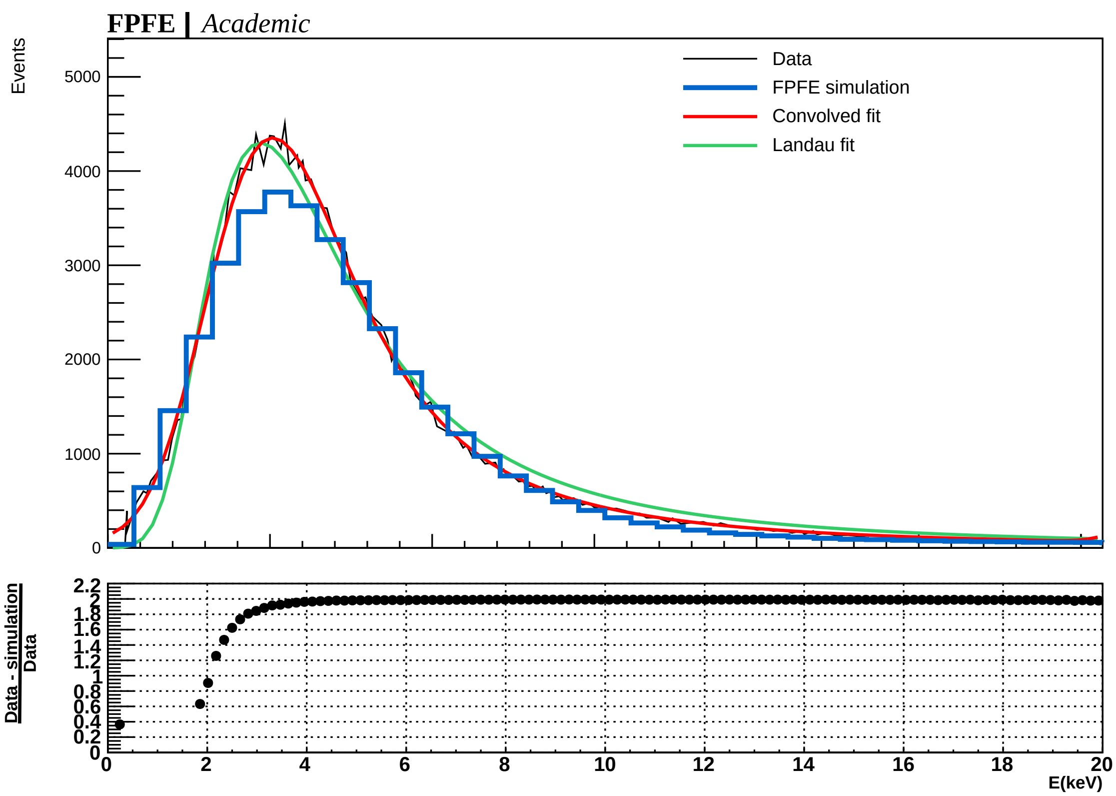


Figure 3: Comparison between the simulation performed in this application (solid blue line) and Meroli's data (solid black line). Two extra fits to the data points were also performed: one of them is just a fit to a landau distribution (solid green line); whereas the other corresponds to the convolution of a gaussian and a landau distribution, according to **eq.** 1. The plot below contains the difference between data and simulation divided by the data and centered around one.

As we can see from this result, the distribution of the simulation does not completely replicate the experimental data. However, we find that one reasonable explanation for this type of behavior might be related to the fact that data was stored in fixed bins and hence we could not exploit any type of binning optimization method to ensure that the plotted results were actually showing an honest comparison between data and simulation. Nevertheless, the results are quite satisfactory, shape wise.

To finish with the comparison, four different simulations were also performed for four different thicknesses of the target: 5.60, 22.40, 56.00 and 112.00 μm, respectively. The normalized results are shown in **Fig.** 4. As the thickness of the target increases, the energy distribution shifts to the right side of the axis. This shift can be easily explained by stating the fact that the thicker the target, the more time the electrons have to

Table 1: Fit parameters for the data distribution.

Fit function	Parameter	Value	Error
Landau + Gaussian	Norm.	29681	451
	MPV	0.9	0.3
	Total Area.	0.227	0.004
	σ	0.253	0.008
Landau	Norm	23800	263
	MPV	1.007	0.006
	σ	0.295	0.004

travel through the target and thus the more energy they loss due to interactions with the material. As for the standardization tendency showed for increasing thicknesses, this behavior could be attached to the fact that for an isotropic material acting as detector, the larger the detector, the worse resolution can be achieved; since most of the EM shower will be contained inside the detector.

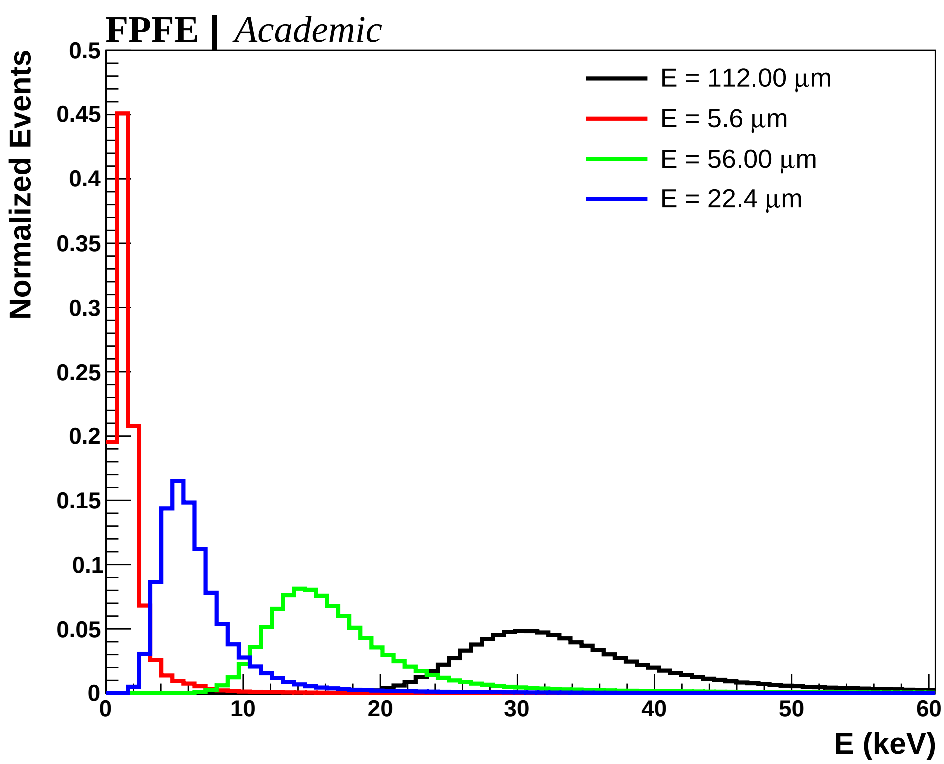


Figure 4: Energy distribution for different thicknesses of the silicon target.

3 A simple model for the CMS calorimeter system

The CMS experiment is a general purpose detector that operates inside the LHC. It is placed at the french commune of Cessy, between lake Geneva and the Jura mountains. Overall, CMS is a 21.6 m detector in length, with a total diameter of 14.6 m. The CMS detector contains four different detectors: **tracker**, **electromagnetic calorimeter** (ECAL), **Hadronic calorimeter** (HCAL) and **muon system**; the first and the latter being tracker systems, whereas the ECAL and the HCAL are the calorimeters in charge of measuring the energy of the particles interating with them.

The ECAL is made up of more than 60000 lead tungstate crystals ($PbWO_4$), and it is in charge of correctly measuring the energy deposited by a charged particle that travels through it. Its main function is to differ between electrons and photons, which are the only particles that can not completely traverse it.

Just following the same principal as with the ECAL, the HCAL of CMS aims to accurately detect hadronic particles and neutrinos, though neutrinos are indirectly detected as missing energy in the event that is being registered. It is built using brass (an alley of copper and zinc) scintillators that basically act as a great barrier that in most cases avoid the pass of these hadronic particles to reach the muon chambers.

In order to reproduce the same scenario as in the CMS detector, the simulation takes into account an adapation of the premises behind the design of the original CMS calorimeter system. Following these ideas, the detector simulation consists in a fully cilyndrical detector construction that is made up of three different materials: vacuum (galactic), lead tungstate and brass (see appendix A). An schematic view of the replica of CMS is shown in **Fig.** 5, and a summary of its characteristics can be found in **Table** 2.

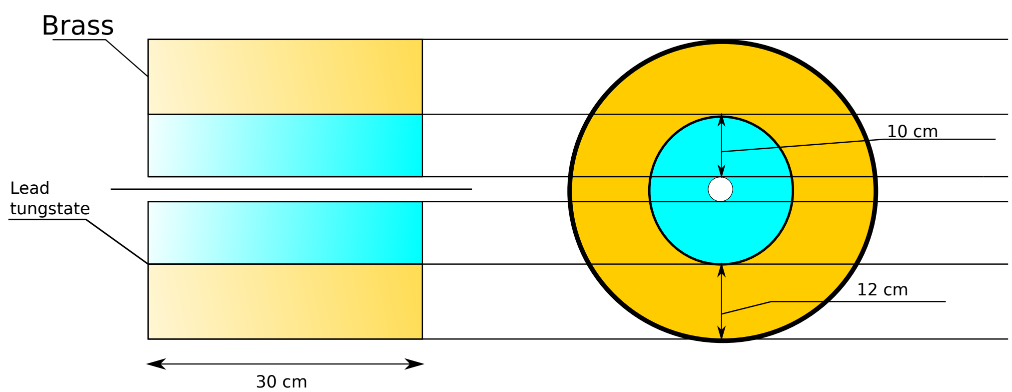


Figure 5: An schematic view of the detector used for replicating the original calorimeter system of CMS.

Table 2: Setup for the CMS replica.

Geometry	r_{inner} (cm)	r_{outer} (cm)	ϕ (rad)	Material
World	0	2	2π	Galactic
ECAL	2	12	2π	$PbWO_4$
HCAL	12	25	2π	Brass
World	25	37.5	2π	Galactic

Once the detector is settled, the only task left to do is to check the performance of our detector. In particular, we are going to study is its ability to stop photons and electrons in the ECAL and pions in the HCAL. If the simulation is correctly settled, the electrons and photons should leave most of its energy in the ECAL, whereas the pions should reach the HCAL easily.

The simulation run over 10k[1] events for three different particles: e^-, γ and π^-, and for three different

[1] The simulation run in a local computer with GEANT4 installed. Simulations of high energy particles took about 10 minutes using 9 off of a 12 core CPU.

energies of these: 100 MeV[2], 1 GeV and 10 GeV. The distribution of fractional energy deposited on each part of the detector can be seen in **Figs.** 6 for the ECAL and 7 for the HCAL. Electrons and photons are found to be completely stoppable up to energies of 1 GeV, leaving a little bit of its energy still in the HCAL (about 0.1%), whereas for e^-/γ with energies up to 10 GeV, a fifth of its energy reaches the HCAL. As for the pions, they interact poorly with both the ECAL and the HCAL, while one would expect them to stop completely in the HCAL. The reason of this behavior can be mainly attributed to the limitations on our simulation: the HCAL is not thick enough to fully condense the hadronic shower produced, thus making it unefficient for stopping low interactive particles such as hadrons.

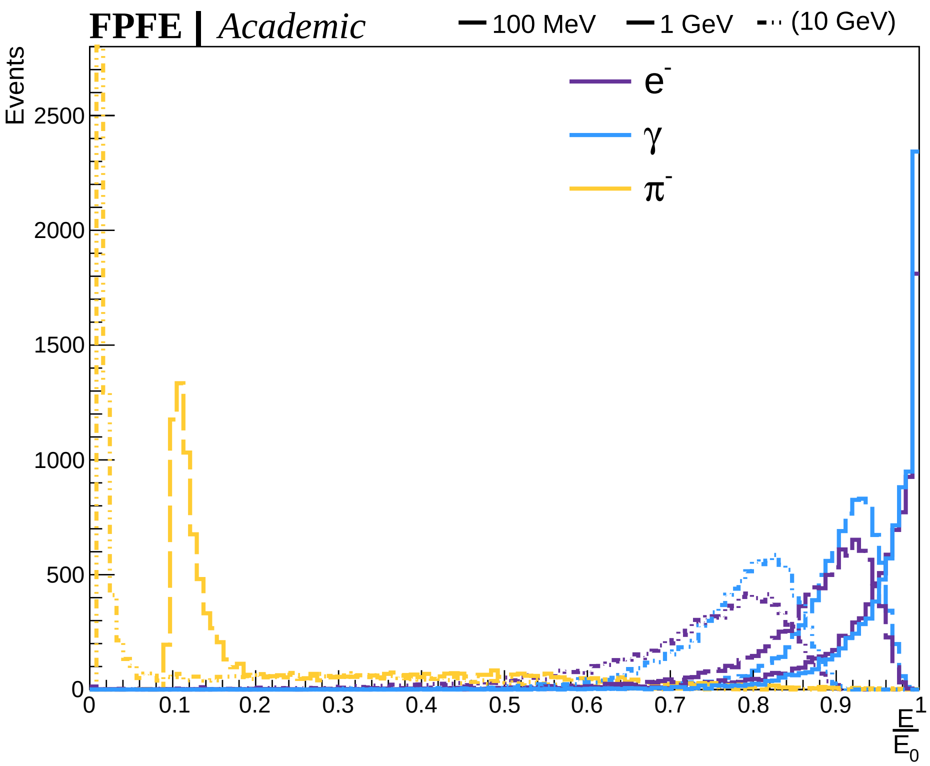


Figure 6: Energy distribution deposited in the ECAL for 100 MeV, 1 GeV and 10 GeV electrons and photons and pions. Note that the X axis corresponds to the fraction of energy deposited by the electromagnetic shower, so all the distributions can be easily compared.

[2]This was not set for pions.

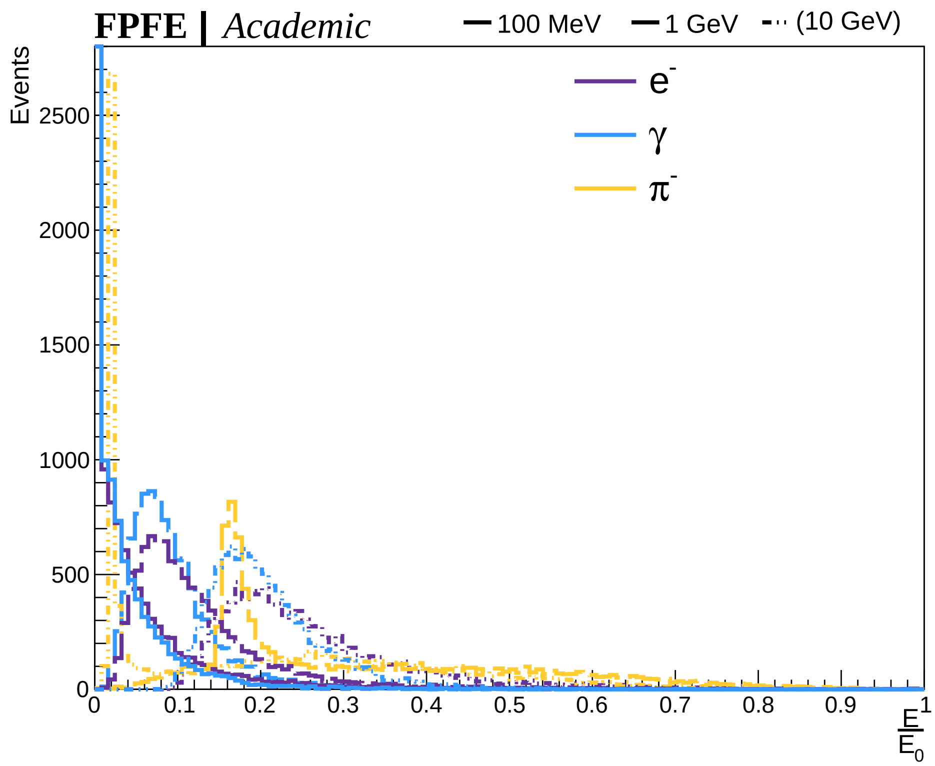


Figure 7: Energy distribution deposited in the HCAL for 100 MeV, 1 GeV and 10 GeV electrons and photons and pions. Note that the X axis corresponds to the fraction of energy deposited by the electromagnetic shower, so all the distributions can be easily compared.

4 Conclusions

In this experimental report, a thorough analysis based on the interactions of particles with different materials have been presented.

In the first part, we have reproduced significantly similar results to those that were published in 2011. We have focused our analysis in just two variables: the deposited energy by the EM shower, and the total track length traveled by particle that originates said shower. We consider to have understood the results in terms of the contents that were seen during the master's lectures.

In the second part, we have presented a simplistic yet valid simulation of a real detector: the CMS detector from the LHC. The results presented in this part show that using materials like $PbWO_4$, characterized by their great density and large radiation length, allow detectors to fully contain electrons and photons, while due to hadrons being much more massive, only a fraction of its initial energy is deposited in the materials. As for the HCAL implementation, though we were not able to fully contain pions inside the HCAL, this is mostly because of limitations on the computational resources, we were able to see the reason why great quantities of brass are required for the design of an efficient HCAL.

The main goal of this project was to perform physics analysis based on GEANT4 simulations, but we consider technical implementation a great part of the work. In particular, in order to obtain the CMS-replica, the implementation of multi-threading simulations has been crucial; not only because of efficiently making use of the computation resources, but also in order to reduce computation time.

References

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[2] Energy loss measurement for charged particles in very thin silicon layers, Meroli, Stefano and Passeri, D and Servoli, L, Journal of Instrumentation, v6-06 (2011), IOP Publishing

[3] Chatrchyan et Al. The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment, CMS Collaboration (2008). DOI:10.1088/1748-0221/3/08/S08004, JINST. Available online at: https://cds.cern.ch/record/1129810. Also published by CERN Geneva in 2010.

[4] Carlos Vico. Geant4 project for Particle Physics at the Energy frontier. Available online at: https://github.com/Cvico/Geant4_project.

[5] CERN. Root reference guide web page. Available online at: https://root.cern.ch/doc/master/index.html

A List of materials

Table 3: List of materials used for the simulations

Used	Detector	Material	Composition
Meroli's	Target	Silicon	100% Silicon (G4_Si)
CMS replica	ECAL	Lead Tungstate	$PbWO_4$
	HCAL	Brass	66% Cu + 34% Zn
All	Vacuum	Galactic	Low pressured gas at 2.7 K

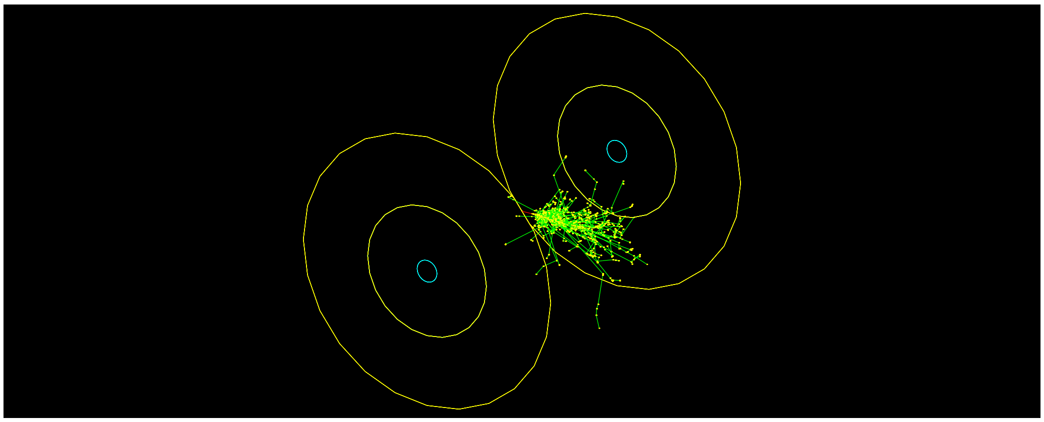

Figure 8: Electromagnetic shower of an electron in the CMS replica simulated in this project.

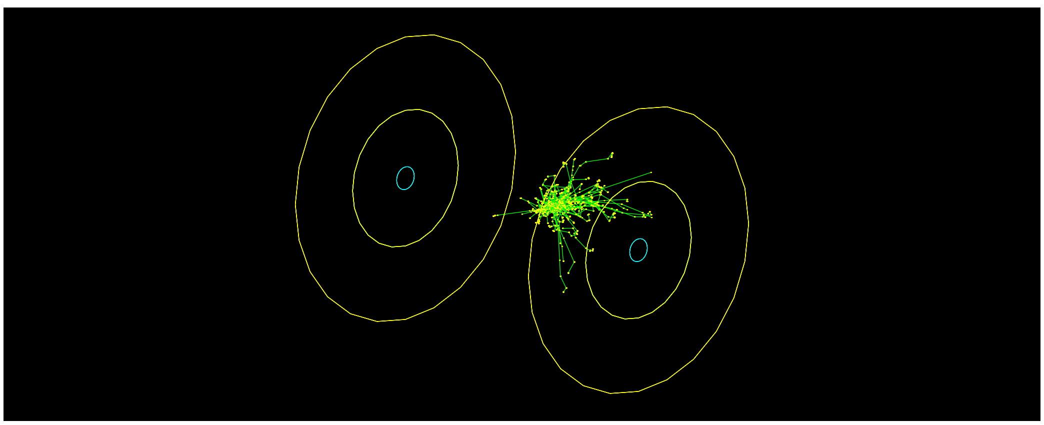

Figure 9: Electromagnetic shower of a photon in the CMS replica simulated in this project.

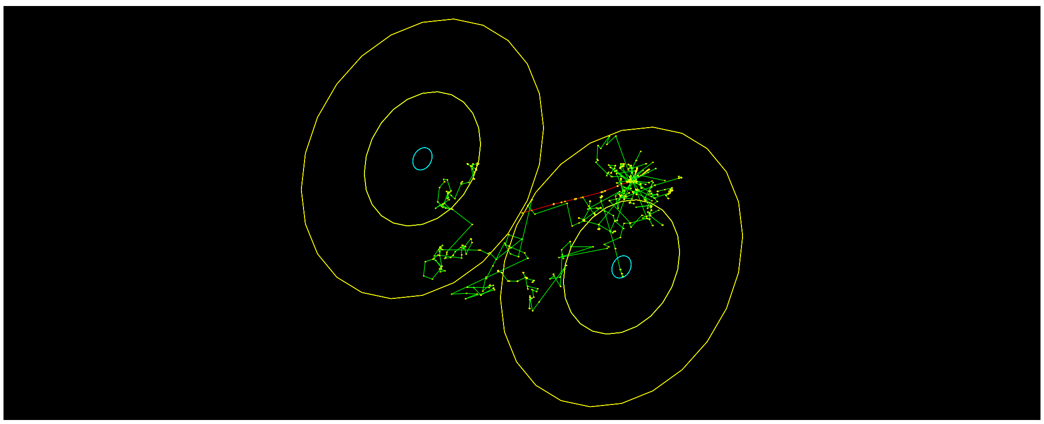

Figure 10: Electromagnetic shower of a pion in the CMS replica simulated in this project.