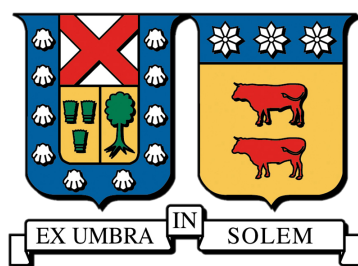

Simulations and analysis for the detection of cosmic rays at the CONDOR Observatory

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ABSTRACT

The detection of high-energy particles is critical for advancing our understanding of the universe and its phenomena. This thesis aims to optimize the forthcoming advancements and detections of the CONDOR Observatory currently under construction by conducting detailed simulations of gamma rays interacting with the Earth's atmosphere, generating extensive air showers that provide a comprehensive description of potential future detections at CONDOR.

In this study, various versions of the CORSIKA simulation software were utilized to validate the use of the specific version employed in this thesis. A primary gamma and cosmic ray with an incident energy of 10^5 GeV, a target detection range for the observatory, was simulated. The resulting data allowed for the graphical representation and analysis of the behavior of various particles of interest, including electrons, photons, and charged particles in general. It was observed that the particles reaching the detector are the least energetic, as the more energetic ones are produced closer to the initial primary particle-atmosphere interactions.

Simulations were also performed for gamma rays incident at different zenith angles, illustrating a decrease in both the quantity and energy of the particles as the zenith angle increased. The resulting plots and thorough analysis confirmed that the proposed 133×112 meter area for the detector array is valid and sufficient for detecting the most important particles under study.

The findings of this research lay a solid foundation for future work incorporating Machine Learning techniques, which hold the potential to significantly advance modern science and particle detection capabilities.

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ABBREVIATIONS

- CONDOR: **C**Ompact **N**etwork of **D**etectors with **O**rbital **R**ange.
- CORSIKA: **C**Osmic **R**ay **S**imulations for **K**Askade.
- VENUS: **V**ery **E**nergetic **N**Uclear **S**cattering.
- QGSJET: **Q**uark-**G**luon **S**tring Model with **J**ETs.
- FLUKA: **FL**Uktuierende **K**Askade or Fluctuating Cascade.
- UrQMD: **U**ltra-**r**elativistic **Q**uantum **M**olecular **D**ynamics.
- CoREAS: **C**orsika-based **R**adio **E**mission from **A**ir **S**hower.

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INTRODUCTION

The detection of high-energy particles as cosmic rays stands as a fundamental discipline in modern astrophysics, allowing us to explore the most extreme and energetic phenomena in the universe. These particles, originating from astrophysical sources such as stars, supernovae, pulsars, black holes, and active galaxies, travel at speeds close to the speed of light and possess energies that far exceed those produced in terrestrial particle accelerators.

The importance of studying these particles lies in their ability to provide crucial information about the physical processes occurring in extreme cosmic environments. For instance, the detection of high-energy cosmic rays provides insights into the acceleration mechanisms in astrophysical sources, the composition of matter in the universe, and the nature of interstellar magnetic fields. Similarly, the observation of high-energy gamma rays allows us to investigate the nature of the most violent and energetic celestial objects, such as supermassive black holes and relativistic jets.

The CONDOR project emerges as a significant scientific endeavor to understand and characterize the high-energy particles constantly bombarding our atmosphere. It will be strategically located in the Atacama Desert, in Northern Chile, CONDOR harnesses the exceptional atmospheric and geographical conditions of this region for the detection of cosmic rays and gamma rays.

The main objective of this thesis is to explore and analyze the behavior of high-energy particles detected by the CONDOR Observatory, through detailed simulations using the CORSIKA software, an essential tool in astrophysical research, as it allows for the simulation of the transport and interaction of cosmic particles in the Earth's atmosphere and on the planet's surface.

Through these simulations, the aim is not just to understand the response of the CONDOR detection system to different energy and atmospheric conditions but also to provide valuable insights for optimizing and calibrating detectors and interpreting real experimental data.

THE STANDARD MODEL OF PARTICLE PHYSICS

To understand cosmic rays detection, it is important to grasp the Standard Model of Particle Physics (SM). The SM is a quantum field based on the ideas of unification and symmetries, which describes the fundamental structure of matter and vacuum considering elementary particles as irreducible entities and as “quanta” of fields (packets of energy and momentum of the fields) whose kinematics are governed by the four known fundamental interactions (excluding

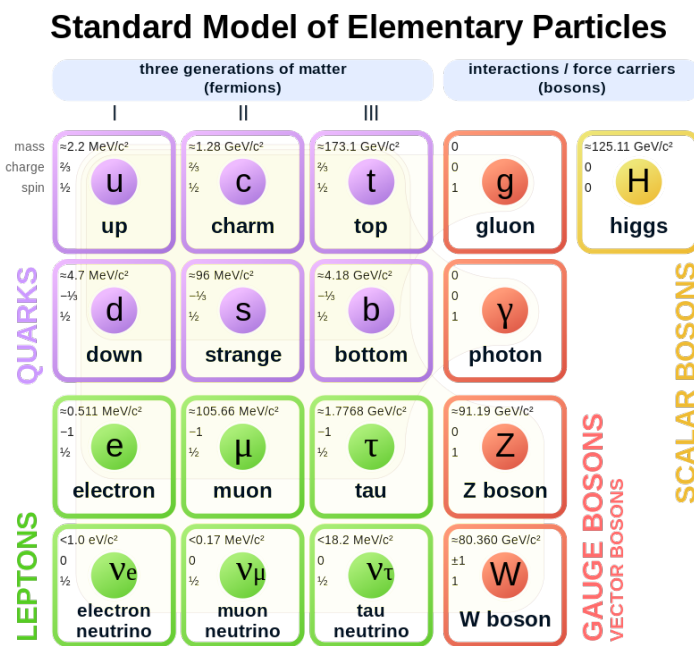


Figure 2.1: Elementary Particles of the Standard Model. Source: Standard Model, Wikipedia.

gravity, whose main theory, general relativity, does not fit with the mathematical models of the quantum world) [4], but it's irrelevant in this study. To date, almost all experimental tests of the three forces described by the standard model agree with its predictions. However, the standard model falls short of being a complete theory of fundamental interactions due to several unresolved issues. The SM includes particles such as quarks, leptons, gauge bosons, and the Higgs boson, and describes three of the four fundamental forces: electromagnetism, strong nuclear force, and weak nuclear force. So let's understand the particles that comprise the SM, (see Fig. 2.1).

2.1 Fermions

The Standard Model includes 12 elementary particles of spin $\frac{1}{2}$, known as fermions [5]. Fermions respect the Pauli exclusion principle [6]. Each fermion has a corresponding antiparticle [7]. They are classified based on how they interact, which is determined by the charges they carry, into two groups: quarks and leptons.

2.1.1 Quarks

There are six quarks: up, down, charm, strange, top, and bottom [5]. Quarks carry color charge, and hence interact via the strong interaction. The color confinement phenomenon results in quarks being strongly bound together such that they form color-neutral composite particles called hadrons; quarks cannot individually exist and must always bind with other quarks [8]. Hadrons can contain either a quark-antiquark pair (mesons) or three quarks (baryons). The lightest baryons are the nucleons: the proton and neutron. Quarks also carry electric charge and weak isospin, and thus interact with other fermions through electromagnetism and weak interaction.

2.1.2 Leptons

The six leptons consist of the electron (e^-), muon (μ^-), tau (τ), electron neutrino (ν_e), muon neutrino (ν_μ), tau neutrino (ν_τ) [9]. The leptons do not carry color charge, and do not respond to strong interaction. The main leptons carry an electric charge of $-e$, while the three neutrinos carry a neutral electric charge. Thus, the neutrinos' motion are only influenced by weak interaction and gravity, making them difficult to observe.

2.2 Bosons

2.2.1 Gauge bosons

The Standard Model includes 4 kinds of gauge bosons of spin 1 [5], with bosons being quantum particles containing an integer spin. The gauge bosons are defined as force carriers, as they are responsible for mediating the fundamental interactions. The Standard Model explains the

four fundamental forces as arising from the interactions, with fermions exchanging virtual force carrier particles, thus mediating the forces. At a macroscopic scale, this manifests as a force [10]. As a result, they do not follow the Pauli exclusion principle that constrains fermions; bosons do not have a theoretical limit on their spatial density. The gauge bosons are photons, which carry the electromagnetic interaction; W and Z bosons, which carry the weak interaction; and gluons, which carry the strong interaction [11].

2.2.2 Higgs boson

The Higgs boson, or Higgs particle, is an elementary particle in the SM produced by the quantum excitation of the Higgs field [12]. In the Standard Model, the Higgs particle is a massive scalar boson with zero spin, even (positive) parity, no electric charge, and no colour charge that interacts with mass. It is also very unstable, decaying into other particles almost immediately upon generation.

The Higgs field is a scalar field with two neutral and two electrically charged components that form a complex doublet of the weak isospin $SU(2)$ symmetry. Its "Mexican-hat potential" leads it to take a nonzero value everywhere (including otherwise empty space), which breaks the weak isospin symmetry of the electroweak interaction and, via the Higgs mechanism, gives a rest mass to all massive elementary particles of the Standard Model, including the Higgs boson itself.

2.3 Fundamental Interactions

2.3.1 Electromagnetism

Electromagnetism is an interaction that occurs between particles with electric charge via electromagnetic fields. It is the dominant force in the interactions of atoms and molecules. Photons mediate the electromagnetic force, responsible for interactions between electrically charged particles. The photon is massless and is described by the quantum electrodynamics (QED) [13].

2.3.2 Strong Nuclear Force

Also called the strong force or strong interaction, is a fundamental interaction that confines quarks into protons, neutrons, and other hadron particles. The strong interaction also binds neutrons and protons to create atomic nuclei, where it is called the nuclear force. Gluons mediate the strong interactions, which binds quarks to each other by influencing the color charge, with the interactions being described in the theory of quantum chromodynamics (QCD). They have no mass, and there are eight distinct gluons, with each being denoted through a color-anticolor charge combination (e.g. red-antigreen). As gluons have an effective color charge, they can also interact amongst themselves.

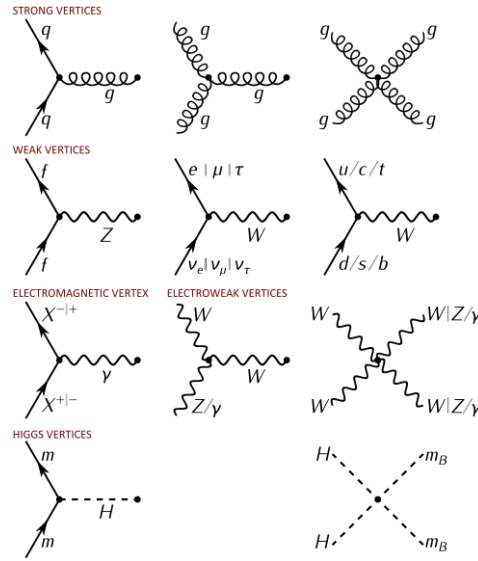


Figure 2.2: Interactions in the Standard Model. q represents any quark, g represents a gluon, X represents any charged particle, γ represents a photon, f represents any fermion, m represents any particle with mass (possibly excluding neutrinos), and m_B represents any boson with mass. Source: Standard Model, Wikipedia.

2.3.3 Weak Nuclear Force

It is the mechanism of interaction between subatomic particles that is responsible for the radioactive decay of atoms: The weak interaction participates in nuclear fission and nuclear fusion. The W^+ , W^- , and Z gauge bosons mediate the weak interactions between all fermions, being responsible for radioactivity. They contain mass, with the Z having more mass than the $W^\pm$. The weak interactions involving the $W^\pm$ act only on left-handed particles and right-handed antiparticles. The $W^\pm$ carries an electric charge of $+1$ and -1 and couples to the electromagnetic interaction. The electrically neutral Z boson interacts with both left-handed particles and right-handed antiparticles. These three gauge bosons along with the photons are grouped together, as collectively mediating the electroweak interaction.

2.3.4 The Lagrangian of the Standard Model

Now, knowing the propagators and the interactions of the Standard Model you can, in principle, calculate the probability of any process in the universe (well, any process not involving gravity). Why quarks stick together in protons, why atoms bind into molecules, why a foot doesn't pass through the floor beneath them—it's all there. In principle; in practice, the calculation requires knowing how to translate these diagrams (See Fig. 2.2) into equations. Below, in simplified notation, is the starting point: the Lagrangian that summarizes all of the propagators and

interactions listed:

$$(2.1) \quad \mathcal{L} = -\frac{1}{4}G^2 - \frac{1}{4}W^2 - \frac{1}{4}F^2 + (\nabla H)^2 + \mu^2 H^2 - \lambda H^2 - \lambda H^4 + i \sum_j \bar{f}_j \nabla f_j - \sum_{jk} c_{jk} \bar{f}_j H f_k.$$

This one equation describes everything we know about the way matter behaves, except, of course, for gravity. In the equation, G describes the gluon field and its interactions, W stands for the $SU(2)$ field (describing the W^+ , W^- , and Z^0 particles and their interactions with each other), F is the $U(1)$ field, H is the Higgs, and f_j is shorthand for all the fermions: electrons, neutrinos, and quarks.

2.3.5 Gamma and Cosmic Rays

Cosmic rays are high-energy particles originating from outer space that constantly bombard the Earth. These particles, which include protons, atomic nuclei, and electrons, travel at nearly the speed of light and possess a wide range of energies. The sources of cosmic rays are diverse, ranging from the Sun (solar cosmic rays) to distant supernovae and other astrophysical phenomena (galactic and extragalactic cosmic rays).

Gamma rays, a type of high-energy electromagnetic radiation, play a crucial role in the study of cosmic rays. Unlike charged particles, gamma rays are not deflected by magnetic fields, allowing them to travel in straight lines from their sources. This property makes gamma rays valuable for tracing back to their origins and studying astrophysical processes. Additionally, gamma rays are produced in significant quantities during the interactions of cosmic rays with the atmosphere, contributing to the extensive air showers¹ (EAS) and providing insight into the nature of cosmic rays.

¹ Cascades of subatomic particles and ionized nuclei, produced in the atmosphere when a primary cosmic ray enters the atmosphere. When a particle of the cosmic radiation, which could be a proton, a nucleus, an electron, a photon, or (rarely) a positron, interacts with the nucleus of a molecule in the atmosphere, it produces a vast number of secondary particles, which make up the shower.

CONDOR OBSERVATORY

The CONDOR¹ observatory is a proposed state-of-the-art facility to be situated at the Atacama Astronomical Park in northern Chile. This observatory aims to be the highest-altitude cosmic and gamma ray observatory in the world, positioning itself at an altitude between 5300 and 5600 meters above sea level.

3.1 Scientific Objectives

The primary objective of the CONDOR observatory is to bridge the sensitivity gap that currently exists between satellite and ground-based telescopes. By doing so, CONDOR will open a new observational window to study the Extreme Universe and the Sun. The scientific program of CONDOR includes: gamma rays in the GeV-TeV region, focusing on transient phenomena such as gamma-ray bursts (GRBs). Multi-messenger astronomy of the Sun, aiming to correlate cosmic ray events with solar activity. Searches for new physics, including investigations into dark matter and other exotic cosmic-ray phenomena.

3.2 Observatory Layout and Detection Mechanism

The layout of the CONDOR observatory is being meticulously optimized. It will consist of an array of detectors designed by Fermilab (see Fig. B.1) to measure the particles produced by cosmic rays interacting with the upper atmosphere (see Fig. B.2). When high-energy gamma rays strike the upper atmosphere, they initiate a cascade or “shower” of secondary particles, which can then be detected at ground level.

¹ The name is also a tribute to the Andean Condor, which is the largest bird of prey in the world and one of the few animals that inhabits the extreme altitudes in the Atacama region (nesting at above 5000 meters a.s.l.).

Due to its extreme altitude, CONDOR will have unprecedented sensitivity to faint signals that are otherwise undetectable at lower altitudes. This capability will significantly enhance the understanding of the cosmic and gamma ray phenomena.

3.3 Technology

The core technology underpinning the CONDOR observatory involves the use of plastic scintillators coupled with wavelength-shifting (WLS) [14] fibers and silicon photomultipliers (SiPMs). This technology has been successfully employed in several other notable experiments, including IceCube, Pierre Auger Prime, and Mu2e [15], [16], [17].

3.3.1 Silicon Photomultipliers (SiPMs)

Photomultipliers (PMTs) are electron tube devices which convert light into a measurable electric current. They are extremely sensitive and, in nuclear and high-energy physics, are most often associated with scintillation detectors, although their uses are quite varied. In solid-state electronics, SiPMs are single-photon-sensitive devices based on single-photon avalanche diodes (SPADs) implemented on common silicon substrate.

SiPMs [18] are crucial to the CONDOR observatory. They replace traditional vacuum PMTs, which are not only expensive and bulky but also fragile and require high voltages to operate. Modern SiPMs contain tens of thousands of pixels within a compact $6 \times 6 \text{ mm}^2$ area, with each pixel functioning as an independent single photon detector (see Fig B.3). These devices have proven their resilience in extreme environments, such as the South Pole (IceCube) and the Argentinean Pampa (Pierre Auger).

3.3.2 Plastic Scintillators

Plastic scintillators [1] serve as the active detection material in the CONDOR observatory. Fermilab produces long, extruded bars of these scintillators, which are integral to the detection array.

The scintillation detector is undoubtedly one of the most often and widely used particle detection devices in nuclear and particle physics today. It makes use of the fact that certain materials when struck by a nuclear particle or radiation, emit a small flash of light; a scintillation. When coupled to an amplifying device such as a photomultiplier, these scintillations can be converted into electrical pulses which can then be analyzed and counted electronically to give information concerning the incident radiation.

A scintillation detector generally consists of a scintillating material which is optically coupled to a photomultiplier either directly or via a light guide (see Fig. 3.1). As radiation passes through the scintillator, it excites the atoms and molecules making up the scintillator causing light to be emitted. This light is transmitted to the photomultiplier where it is converted into a weak

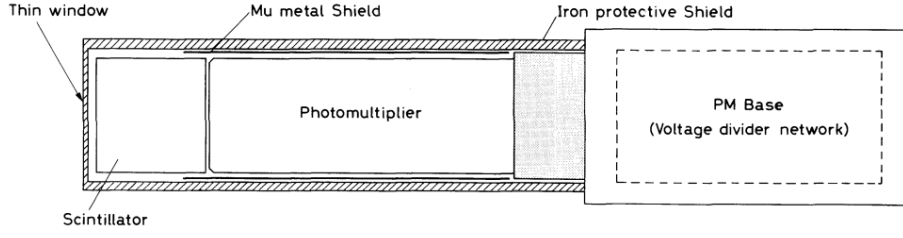


Figure 3.1: Schematic diagram of a scintillation counter [1].

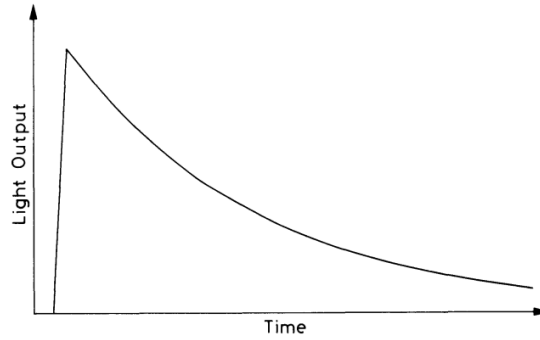


Figure 3.2: Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time [1].

current of photoelectrons which is then further amplified by an electronmultiplier system. The resulting current signal is then analyzed by an electronics system.

Scintillator materials exhibit the property known as luminescence. Luminescent materials, when exposed to certain forms of energy, for example, light, heat, radiation, etc., absorb and reemit the energy in the form of visible light. If the reemission occurs immediately after absorption or, more precisely, within 10^{-8} [s], the process is usually called fluorescence. However, if reemission is delayed because the excited state is metastable², the process is called phosphorescence or afterglow. In such cases, the delay time between absorption and reemission may last anywhere from a few microseconds to hours depending on the material.

As a first approximation, the time evolution of the reemission process may be described as a simple exponential decay (see Fig. 3.2)

$$(3.1) \quad N = \frac{N_0}{\tau_d} \exp\left(-\frac{t}{\tau_d}\right),$$

where N is the number of photons emitted at time t , N_0 the total number of photons emitted, and τ_d the decay constant.

² State of the system that is stable for a prolonged period but not permanently. An excited state being metastable means that the system (such as an atom or molecule) has absorbed energy and moved to a higher energy state, where it remains for an extended period before eventually returning to its ground state.

In nuclear and particle physics, plastic scintillators are probably the most widely used of the organic detectors today. Like the organic liquids, plastic scintillators are also solutions of organic scintillators but in a solid plastic solvent. The most common and widely used plastics are polyvinyl toluene, polyphenylbenzene and polystyrene [19].

Plastics offer an extremely fast signal with a decay constant of about 2 - 3 [ns] and a high light output. Because of this fast decay, the finite rise time cannot be ignored in the description of the light pulse as was done in (3.1). The best mathematical description, as shown by Bengtson and Moszynski [20], appears to be the convolution of a Gaussian with an exponential

$$(3.2) \quad N(t) = N_0 f(\sigma, t) \exp\left(\frac{-t}{\tau}\right),$$

where $f(\sigma, t)$ is a Gaussian with a standard deviation σ .

3.3.3 White Rabbit

White Rabbit is a technology developed by CERN in collaboration with other scientific institutions and companies. It is a high-precision, deterministic Ethernet-based network that combines time synchronization, determinism, and data communication in a single network. White Rabbit can synchronize thousands of nodes with sub-nanosecond precision and accuracy within a few picoseconds [21]. This makes it an essential tool for scientific experiments that require extremely precise synchronization.

White Rabbit utilizes a combination of technologies such as the Precision Time Protocol (PTP) and cable delay compensation to achieve precise synchronization between nodes [22]. It ensures predictable data packet delivery times, which is crucial for real-time control systems. Being compatible with Ethernet, White Rabbit can be easily integrated into existing network infrastructures. Additionally, its scalability allows for the synchronization of thousands of nodes over a wide network, making it ideal for large scientific installations.

At CERN, White Rabbit is used in the Large Hadron Collider (LHC) and other experiments to synchronize events and data acquisition systems [23]. Precise synchronization is essential for correlating data collected by different detectors and ensuring that measurements are accurate and consistent.

The CONDOR Observatory, like many other advanced scientific experiments, requires precise synchronization of its detection systems. CONDOR needs to synchronize multiple detectors spread over a wide area to correlate high-energy events that arrive at different detectors at slightly different times. White Rabbit can provide the sub-nanosecond synchronization necessary for this purpose. To correctly interpret the data from EAS simulations and real detections, it is crucial that all measurements are recorded in a coherent time frame. White Rabbit ensures that all devices on the network share the same time reference.

As CONDOR grows and adds more detectors, White Rabbit will allow for easy network expansion while maintaining precise synchronization and data integrity. Its deterministic nature

provides real-time control of detectors and other devices in the observatory. So, White Rabbit provides the synchronization and communication infrastructure necessary for scientific projects like the CONDOR Observatory to operate effectively and accurately. Its ability to maintain precise timing across a wide, scalable network makes it an ideal choice for CONDOR's high-energy particle detection and analysis needs.

3.4 Design and Efficiency

The detector design for CONDOR is being optimized to ensure high efficiency, particularly in registering low-energy photons. This enhancement will increase the observatory's sensitivity to low-energy cosmic rays. The surface detectors are designed to be inexpensive, modular, robust, and low-maintenance. They will feature a time resolution on the order of 1 nanosecond, a dynamic range of 1-10,000 Minimum Ionizing Particles (MIPs), and a power consumption of less than 500 milliwatts.

3.5 Scientific Contributions and Collaboration

The energy range of CONDOR (sub-TeV) is particularly suited for contributing to multi-messenger astronomy, complementing observations from facilities that cover different light frequencies or gravitational waves. The observatory's sensitivity will be fine-tuned to detect the lowest energies measurable at ground level, thus complementing other high-energy facilities such as the Southern Wide-field Gamma-ray Observatory and the ALPACA observatory [24], [25].

Additionally, the CONDOR observatory collaborates with the Centro Científico Tecnológico de Valparaíso (CCTVal) of the Universidad Técnica Federico Santa María. Researchers and engineers from CCTVal installed the first device of the observatory, enabling a new window for exploring the universe from Chilean soil. This partnership enhances CONDOR's scientific contributions by incorporating advanced technologies such as silicon photomultipliers and the White Rabbit time synchronization technology, to achieve sub-nanosecond precision in particle detection.

CONDOR will provide an all-sky, continuous view of the Southern sky down to 100 GeV, capable of triggering observations from more sensitive instruments with limited fields of view, such as the Cherenkov Telescope Array [26], which is currently under construction in Chile.

CORSIKA FOR EAS SIMULATIONS

Analyzing experimental data on EAS or planning corresponding experiments requires a detailed theoretical modeling of the cascade which develops when a high energy primary particle enters the atmosphere (see Fig. 4.1). This can only be achieved by detailed Monte Carlo calculations, taking into account all knowledge of high energy strong and electromagnetic interactions.

Therefore, a number of computer programs has been written to simulate the development of EAS in the atmosphere and a considerable number of publications exists discussing the results of such calculations.

A common feature of all these publications is that it is difficult, if not impossible, to ascertain in detail which assumptions have been made in the programs for the interaction models, which approximations have been employed to reduce computer time, how experimental data have been converted into the unmeasured quantities required in the calculations, etc.

CORSIKA is a program for detailed simulation of EAS initiated by high energy cosmic ray particles [2]. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries¹.

Particles are tracked through the atmosphere until they either undergo reactions with air nuclei or, in the case of unstable secondaries, decay. High-energy hadronic interactions can be described using several alternative reaction models. The VENUS [27] and QGSJET [28] models are based on Gribov-Regge Theory [29], while SIBYLL is a minijet model [30]. The neXus model extends beyond a simple combination of QGSJET and VENUS routines. The latest EPOS model [31], based on the neXus framework, includes significant improvements concerning hard interactions and nuclear and high-density effects. HDPM [32], inspired by findings of the Dual

¹ Particle (or ray) that collides with the atmosphere.

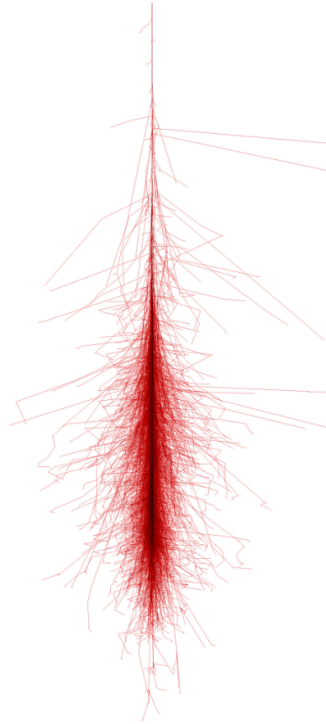


Figure 4.1: Extensive Air Shower (xz-projection) for a photon with initial energy of 100 [GeV]. Source: CORSIKA Shower Images: Photon Showers.

Parton Model, aims to reproduce relevant kinematic distributions measured at colliders (but this is a different kettle of fish).

Lower-energy hadronic interactions are described by the GHEISHA interaction routines [33], by a link to FLUKA [34], or by the microscopic UrQMD model [35]. In particle decays, all decay branches down to the 1% level are taken into account. For electromagnetic interactions, a tailor-made version of the EGS4 shower program or the analytical NKG formulas may be used [36], [37]. Options exist for generating Cherenkov Radiation² and neutrinos [38]. The radio emission of showers can be treated by linking with the CoREAS code [39].

4.1 Program frame

4.1.1 Control and run

At the beginning of the calculation a variety of parameters can be chosen to control the simulation. The primary particle type has to be defined, and its energy can be prechosen or selected at random in a particular energy range with a given slope of the energy spectrum. This allows a realistic simulation of the shower rate falling steeply with rising energy. A simplified flow diagram is given in Appendix A.

² A form of energy that can be perceived as a blue glow emitted when electrically charged particles move faster than light in a specific medium.

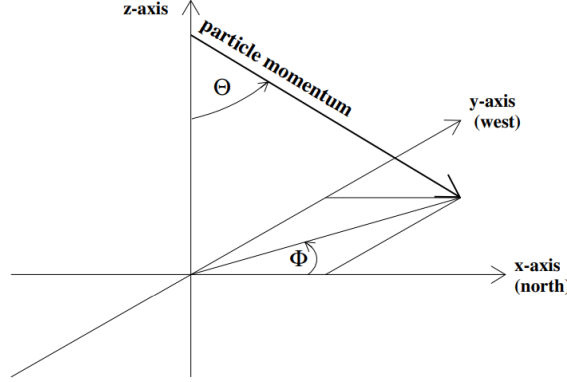


Figure 4.2: CORSIKA's coordinate system [2].

4.1.2 Particles

CORSIKA recognizes 50 elementary particles, like γ , $e^\pm$, $\mu^\pm$, π^0 , $\pi^\pm$, $K^\pm$, $K_{S/L}^0$, η , the baryons p , n , Λ , $\Sigma^\pm$, Σ^0 , Ξ^0 , $\Xi^\pm$, Ω^- , the corresponding anti-baryons, the resonance states $\rho^\pm$, ρ^0 , $K^{*\pm}$, K^{*0} , $\bar{K}^{*0}$, Δ^{++} , Δ^+ , Δ^0 , Δ^- , with their corresponding anti-baryonic resonances, etc. All these particles can be tracked through the atmosphere, are able to interact, annihilate or decay, and produce secondary particles (resulting in the shower). They are fully defined in the program by their particle identification, the Lorentz factor, the zenith and azimuthal angle of the trajectory, the time since the first interaction of the primary, and the three spatial coordinates x , y and z .

4.1.3 Coordinate system

The coordinates are defined with respect to a cartesian coordinate system with the positive x -axis, pointing to the magnetic north, the positive y -axis to the west, and the z -axis upwards. The origin is located at sea level. The zenith angle θ of a particle trajectory is measured between the particle momentum vector and the negative z -axis, and the azimuthal angle ϕ between the positive x -axis and the x - y -component of the particle momentum vector proceeding counterclockwise, (see Fig. 4.2).

4.1.4 Atmosphere

The atmosphere adopted consists of N_2 , O_2 , and Ar with the volume fractions of 78.1%, 21.0% and 0.9% [40]. The density variation of the atmosphere in this model is defined by 5 layers. The boundary of the atmosphere in this model is defined at the height in the lower four of them. The density follows an exponential dependence on the altitude leading to a relation between the mass overburden $T(h)$ of the atmosphere and the height h of the form

$$(4.1) \quad T(h) = a_i + b_i e^{-h/c_i} \quad i = 1, \dots, 4.$$

The parameters a_i , b_i and c_i are selected in a manner that the function $T(h)$ is continuous at the layer boundaries and can be differentiated continuously. And, in the fifth layer ($i = 5$), $T(h)$ decreases linearly with height, as

$$(4.2) \quad T(h) = a_5 - b_5 \frac{h}{c_5}.$$

4.1.5 The Monte Carlo Method

Monte Carlo method [41], also known as multiple probability simulation, is a mathematical technique used to estimate the possible outcomes of an uncertain event. The Monte Carlo method was invented by John von Neumann and Stanislaw Ulam during World War II to improve decision making under uncertainty. It is named after a well-known district of Monaco famous for its casino, as the element of luck is the basis of the modeling approach, similar to a roulette game. This method is a general procedure for selecting random samples from a population (finite or infinite) whose probability distribution is known by random numbers³. Computers, and even some pocket calculators, generate pseudorandom numbers through arithmetic operations from an initial value that is taken as a seed. Although these numbers are not exactly random, as they are determined by the seed, they satisfy the property that each digit has an equal probability of appearing, and they are widely used in practice.

In this context, CORSIKA is operated with the random number generator RANMAR [42] in the version as implemented in the CERN program library [43] which represents the state of the art in computational physics. It is a pseudo random number generator delivering uniformly distributed numbers. It offers the possibility to generate simultaneously up to $9 \cdot 10^8$ independent sequences with a sequence length⁴ of $\approx 2 \cdot 10^{44}$ each. The generator is written in standard FORTRAN [44] and, thus, portable to all types of computers where bit-identical results are obtained.

³ Sets of numbers constructed in such a way that all digits have the same probability of appearing.

⁴ Refers to the number of values the generator can produce before the numbers start repeating.

SIMULATIONS AND ANALYSIS

5.1 Validation Plots

In order to ensure the accuracy of the subsequent plots obtained through simulations, it is important to validate them. "*Validation of Electromagnetic Showers in CORSIKA 8*" [3] will be a useful tool for this purpose, as this article performs a similar validation by comparing CORSIKA 7 with CORSIKA 8. Specifically, version 7.7500 will be used in this study, with EPOS LHC model for high energy hadronic interactions and UrQMD 1.3cr for low energy hadronic interactions. Therefore, it is necessary to apply the same initial configurations used in the article and compare the obtained plots. If they are equal (or similar), then the subsequent plots would be valid.

5.1.1 Longitudinal Profiles

Fig. 5.1 shows the longitudinal profiles¹ from the article mentioned of charged particles and photons for 5000 electromagnetic showers with a primary electron of 100 EeV and a particle cut² of 100 TeV with and without the LPM effect [45] option, the x-axis represents the atmospheric depth in grams per square centimeter (g/cm^2), known as "grammage". This measure is used to indicate how much atmospheric material a particle has traversed while traveling through the atmosphere.

Thus, in Fig. 5.1, it can be observed that the charged particles reach a peak of 40.000 particles, while the photons reach 50.000; the same happens in the validation plot of Fig. 5.2, where it can also be noted that both figures exhibit the same behavior.

¹ Number of particles at different depths in the atmosphere.

² Minimum energy that can be "detected" by the simulation.

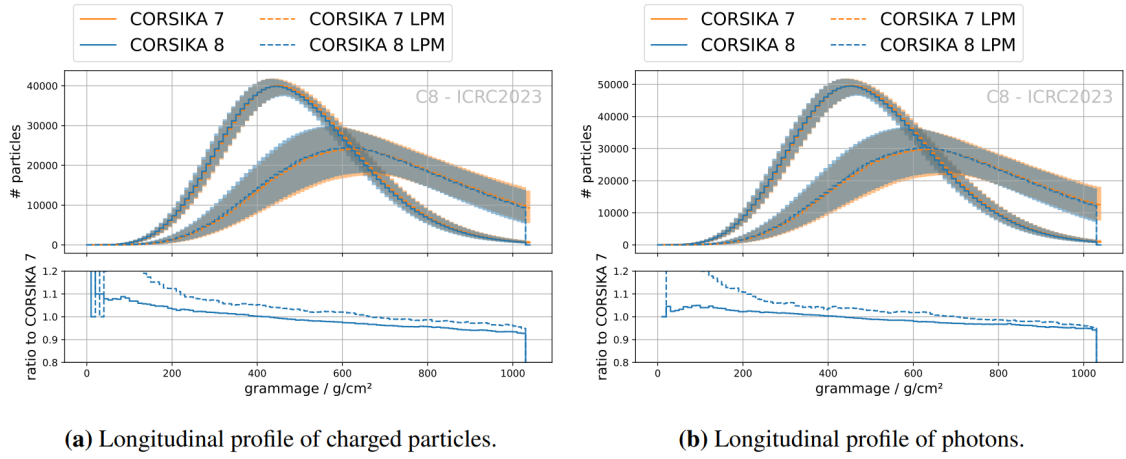


Figure 5.1: Longitudinal profiles for 100 EeV electromagnetic showers with a particle cut of 100 TeV. The showers without the LPM effect are shown in solid lines, while the showers with LPM Effect are shown in dashed lines [3].

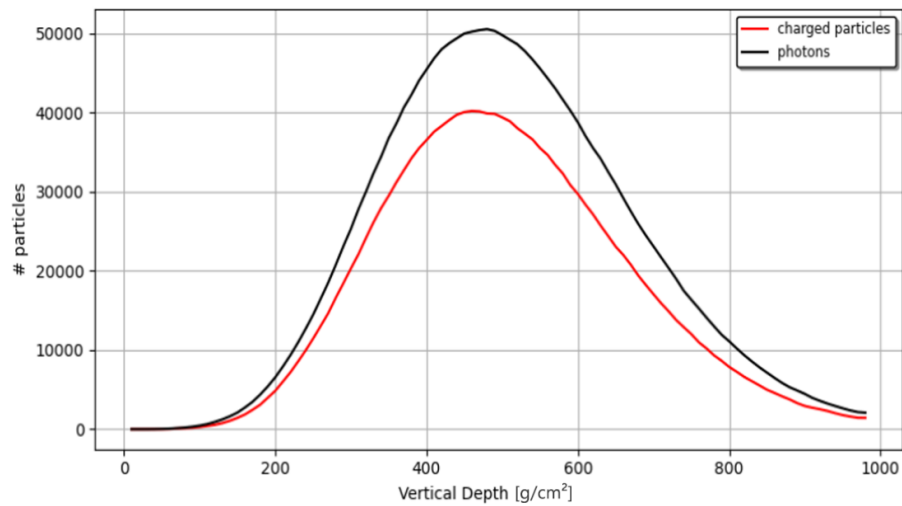


Figure 5.2: Longitudinal profiles in CORSIKA 7.7500 of electromagnetic showers for 100 EeV, comparing the number of charged particles and photons as a function of vertical depth.

5.1.2 Energy Spectra

This is not all; the obtained plots can also be validated by comparing the energy distributions³ (or energy spectra) for the generated particles. In the mentioned article, the energy spectra of a 100 TeV electron shower can be seen in Fig. 5.3, where it can be observed that the number of photons reaches its maximum at the lowest energy values ($\approx 10^{-3}$ GeV), while most charged particles reach their peak at $\approx 10^{-2}$ to 10^{-1} GeV.

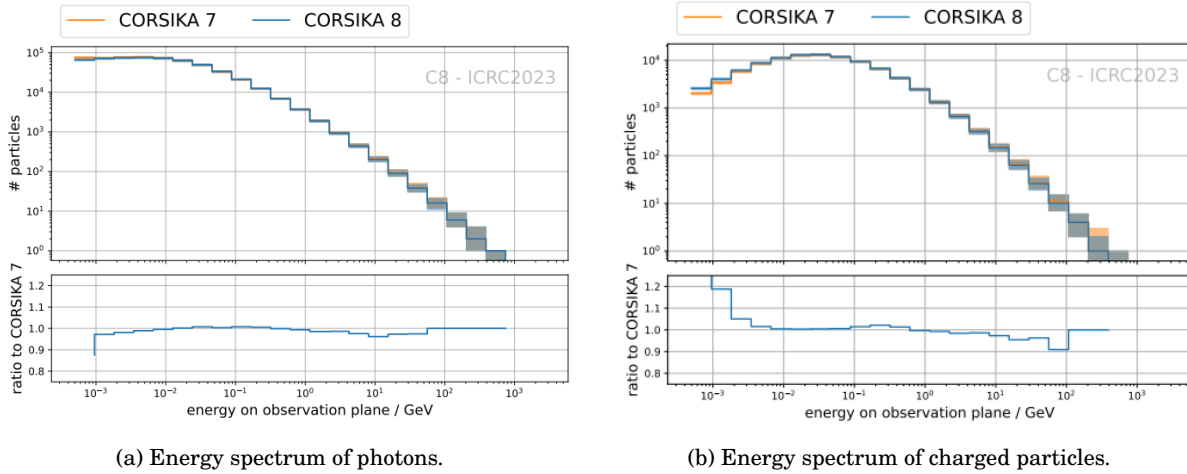


Figure 5.3: Energy spectra of a 100 TeV shower [3].

Now, with Corsika 7.7500, the energy spectra that were obtained are in Fig. 5.4, and it can be seen that both graphs maintain the same behaviors. The only difference is in the number of particles, which could be due to differences in atmospheric conditions, the hadronic interaction models used, or many other factors. However, the important point is that both energy spectra are similar. Therefore, it can be said that the version used for this study is valid and accurate for future simulations.

5.2 Simulations

In addition to energy spectra and longitudinal profiles, it is also quite important to understand the behavior of particles through their spatial distributions. The distributions of electrons, photons, muons, and charged particles, in general, contain the most relevant information about particle cascades. Therefore, plotting these distributions could, in a way, predict what will happen at the CONDOR Observatory and thus be ahead of future detections.

As explained in the corresponding section 4.1.3 about CORSIKA coordinates, the cascade is shown in the YZ projection, while the spatial distribution observed in the detector is in the

³ Number of particles belonging to certain energy ranges (bins).

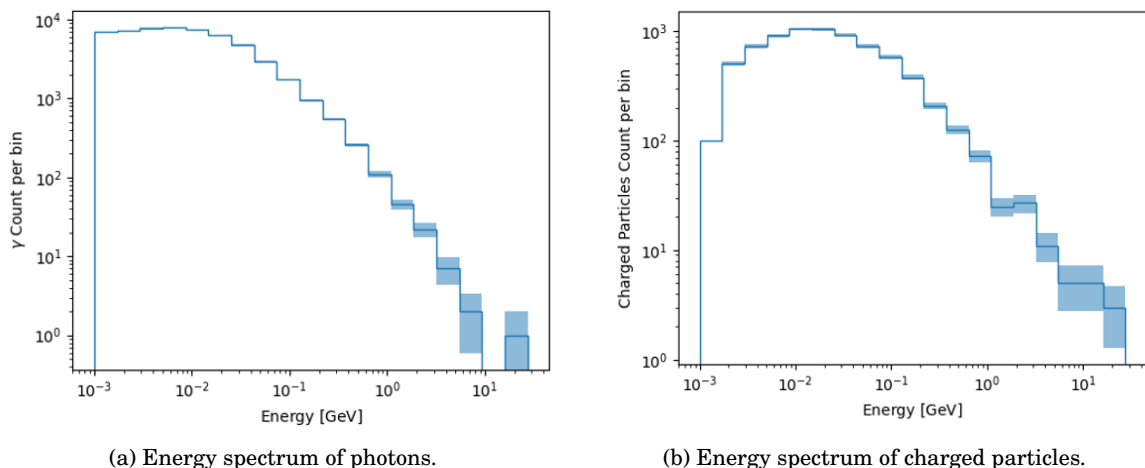


Figure 5.4: Energy spectra of a 100 TeV shower in Corsika 7.7500.

XZ projection (take Fig. 5.5 as an example). So, take a look at the graphics obtained for these particles, starting with the protagonist: the gamma ray.

But first, it is important to highlight the specifications for the simulations. So; 0.3, 0.1, 0.00005, 0.00005 [GeV] are the cut-off energies for hadrons, muons, electrons, and photons respectively. The altitude above sea level will be 5300 [m], to simulate the expected altitude of the CONDOR observatory. All the shown and forthcoming simulations are for incident particles with a 0° zenith and azimuth angle. For the magnetic field, as it does not significantly affect the simulations, the Central Europe values will be used, with $B_x = 20.0$ [μ T] and $B_z = 42.8$ [μ T] [46]. The incident particle energy will be 10^5 [GeV].

5.2.1 Gamma ray

Fig 5.5 provides a detailed analysis of the electrons cascade and spatial distribution graphics obtained through simulations with the CORSIKA program, with the primary particle in this case being a photon. The presented graphs are scaled; all cascades are plotted within $Y = -0.01$ to 0.01 [m] and $Z = 0$ to 1 [m], while the spatial distributions are limited to a range of 113×122 [m^2] (see Fig. 5.5 as an example). This is primarily because these are the areas of interest that will be detected by CONDOR.

However, the complete cascade and spatial distribution should not be overlooked to understand the general behavior of the EAS (Fig. 5.6). It can be seen that most particles concentrate in the "center" of the distribution, as well as the most energetic ones.

The number of electrons appears to be greater than that of positrons. This can be confirmed with the particle count distribution in the simulation (see Fig. 5.7). As expected, the largest number of particles present in the simulation are photons, followed by electrons, which, indeed, are more than positrons (but not as much as it seemed). Muons, antimuons and neutrons are also

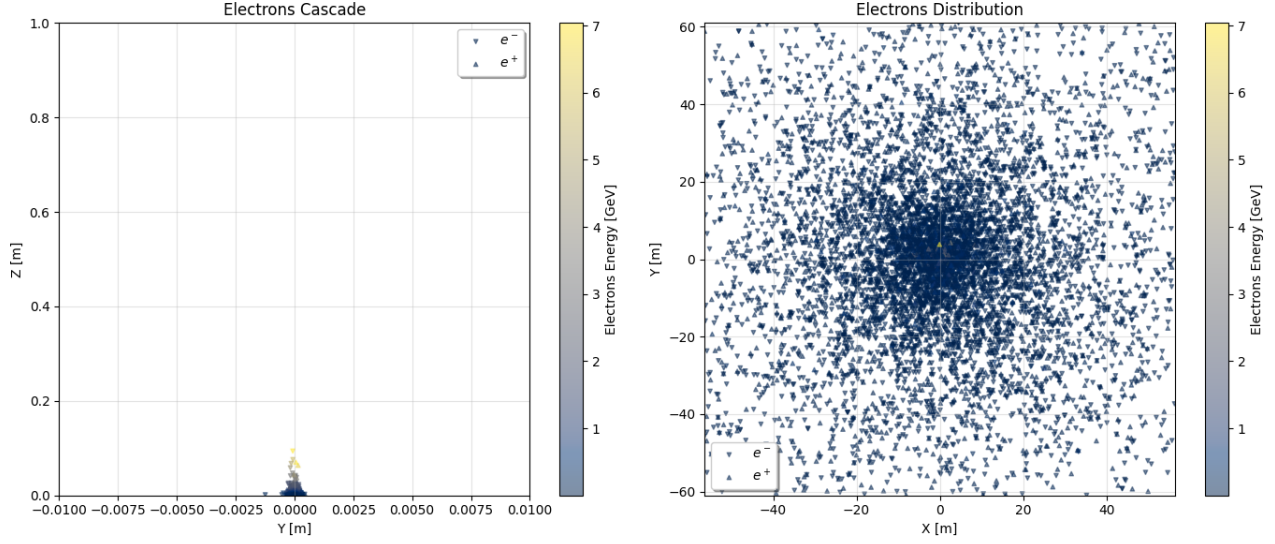


Figure 5.5: Electron Cascade and Spatial Distribution for a gamma ray with 10^5 [GeV] incident energy, also plotted in relation to the detected energy of each electron. Upward triangles correspond to positrons and downward triangles to electrons.

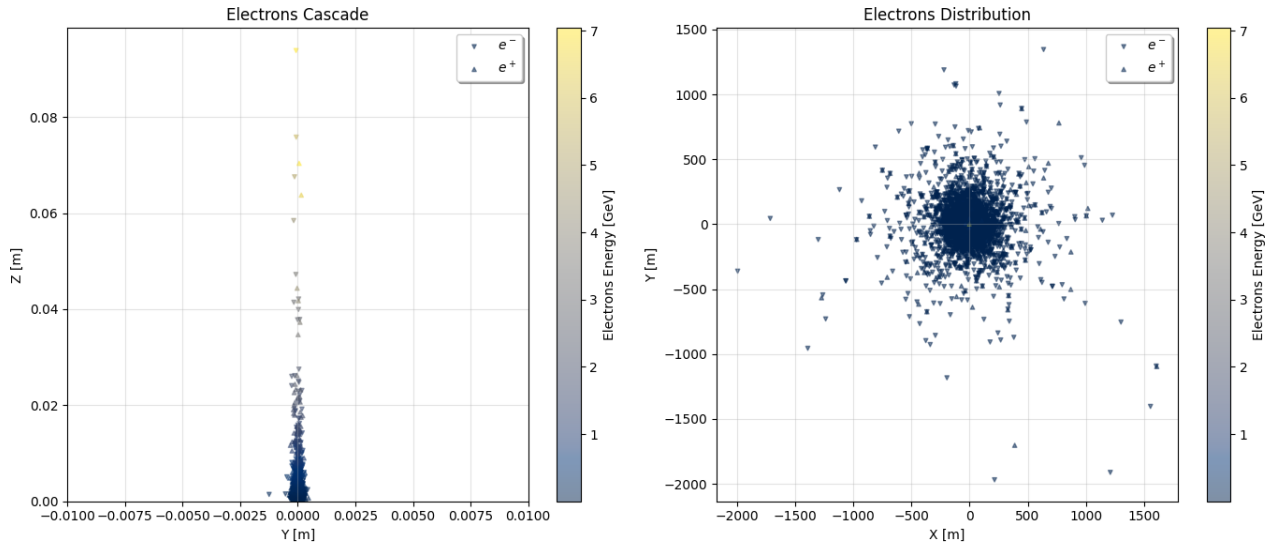


Figure 5.6: Electron Cascade and Spatial Distribution *unscaled* for a gamma ray with 10^5 [GeV] incident energy.

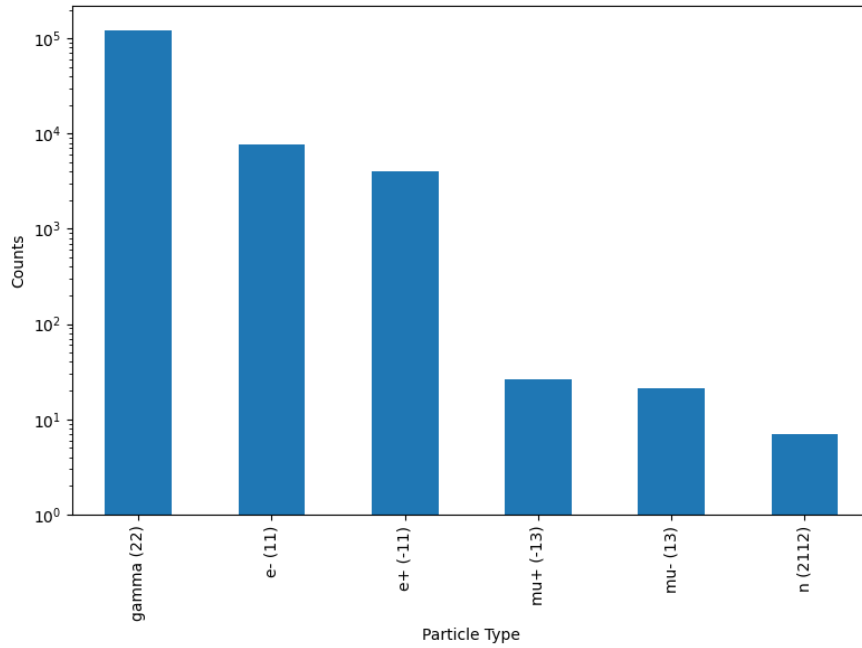


Figure 5.7: Particle count distribution for a gamma ray con 10^5 [GeV] incident energy. The number in parentheses corresponds to the numerical identification of each particle used in CORSIKA.

formed, although in much smaller quantities.

As mentioned previously, the cascade of charged particles is the one that provides the greatest amount of information, since it is what the CONDOR observatory will ultimately detect, so see Fig. 5.8 por the scaled version and Fig. 5.9 for the unscaled. This is where can be seen the behavior of the vast majority of particles generated by the primary particle.

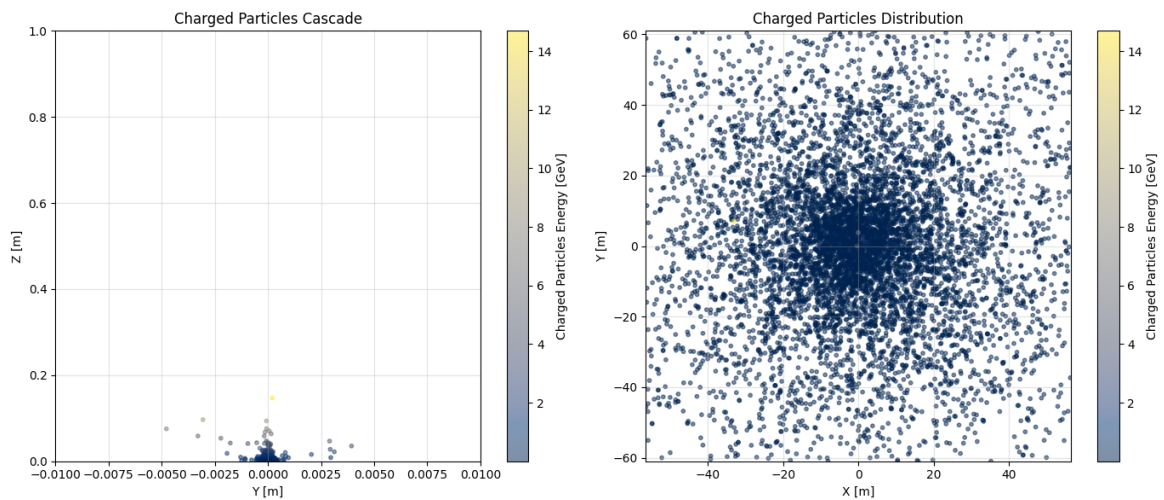


Figure 5.8: Charged Particles Cascade and Spatial Distribution for a gamma ray with 10^5 [GeV] incident energy, also plotted in relation to the detected energy of each particle.

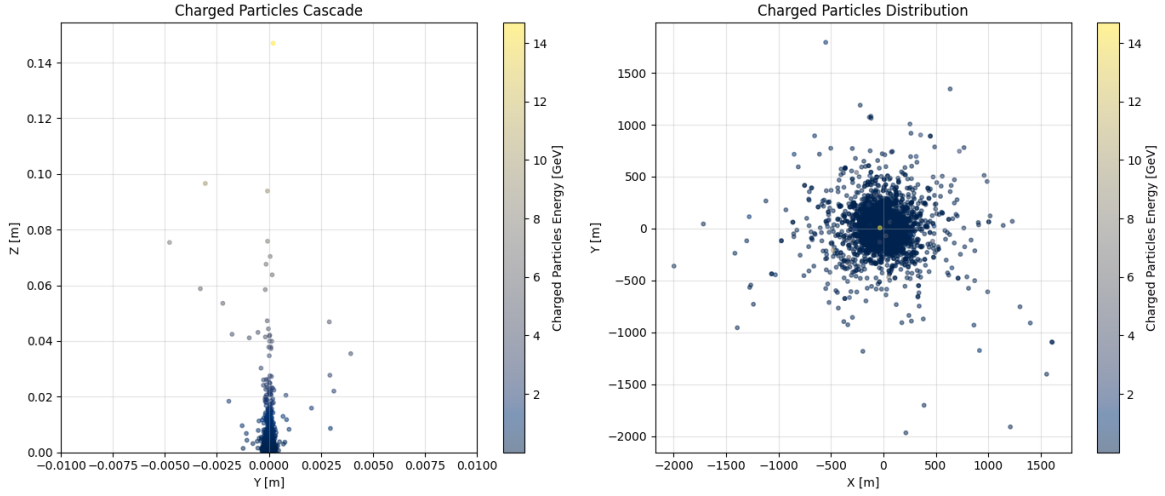


Figure 5.9: Charged Particles Cascade and Spatial Distribution *unscaled* for a gamma ray with 10^5 [GeV] incident energy.

It seems that the first interaction of the incident photon occurred at 0.14 [m] height, which may make sense due to the low energy of its incidence, thus resulting in low interaction probabilities. So, finally, to confirm the behavior of the most important particles, let's examine how the photons produced by this primary photon behave (See Fig. 5.10 for scaled graphs and 5.11 for unscaled).

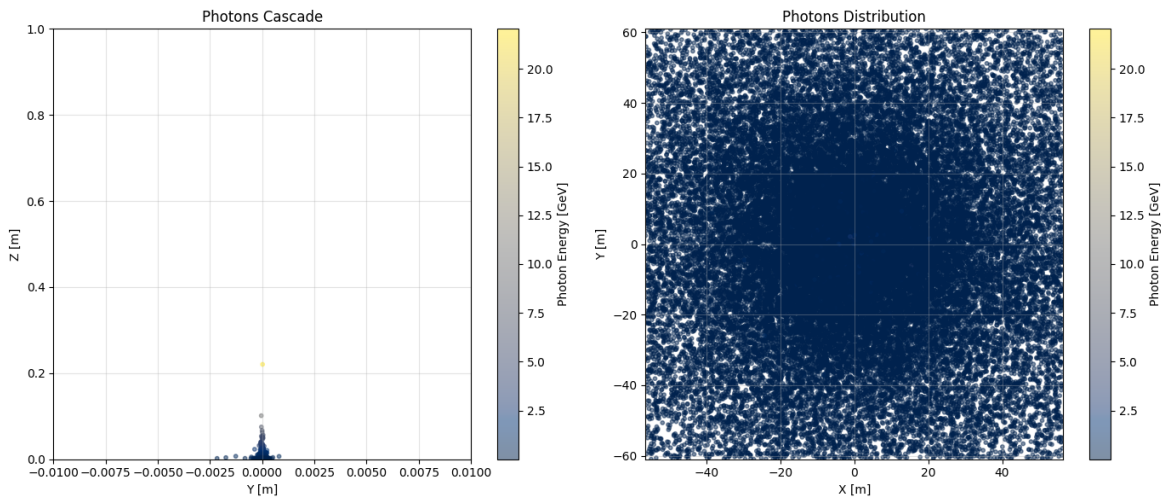


Figure 5.10: Photons Cascade and Spatial Distribution for a gamma ray with 10^5 [GeV] incident energy, also plotted in relation to the detected energy of each particle.

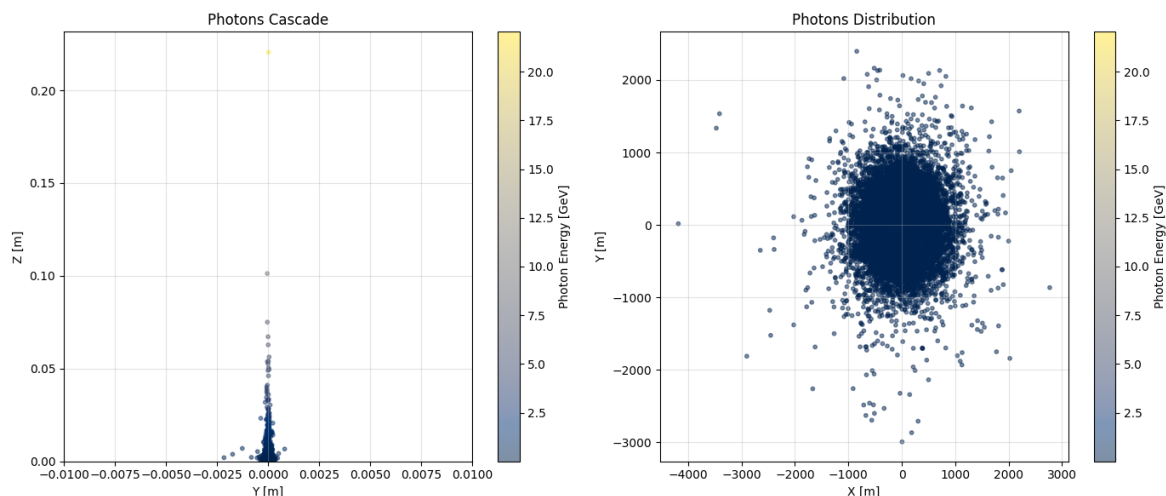


Figure 5.11: Photons Cascade and Spatial Distribution for a gamma ray with 10^5 [GeV] incident energy.

From the graphs, it is clear that this is the most prevalent particle and also the one containing the highest energy particle ($E \approx 20.0$ [GeV]) of all. As seen in Fig. 5.11, this particle is located at the highest altitude ($Z \approx 0.25$ [m]) and is, therefore, the first result of the initial interaction.

Now that the spatial distribution graphs have been analyzed, it's important to also look at the energy spectra produced by the photon (see Fig 5.12).

So, as expected and as observed in the previous graphs, the most energetic particles are the photons. However, it is important to note that the charged particles also tend towards higher energy values, but this is less noticeable due to their smaller quantity.

Now that the behavior of an incident primary photon with 10^5 GeV energy has been observed, it is time to examine how the charged particle cascade behaves, maintaining the same previous specifications but altering the incidence angles of the photon in question.

In the interest of maintaining order, all behavior of charged particles with varying zenith angles can be found in Appendix C. It can be observed that as the incidence angle increases, the number of generated particles decreases. This is because larger incidence angles result in longer atmospheric paths for the particles, causing more interactions and energy losses before reaching the detector, thereby reducing the overall number of secondary particles.

5.2.2 Cosmic Ray

Finally, as discussed in this project, it is necessary to understand the behavior of a cosmic ray when it enters the atmosphere and how the resulting distributions differs with a gamma ray. This knowledge allows for the differentiation of the incidence between these two types of rays. In this case, as discussed in section 2.3.5, a proton will be used as the incident particle, with the same specifications used for the gamma ray, except for the change in the particle itself. Enough talk,

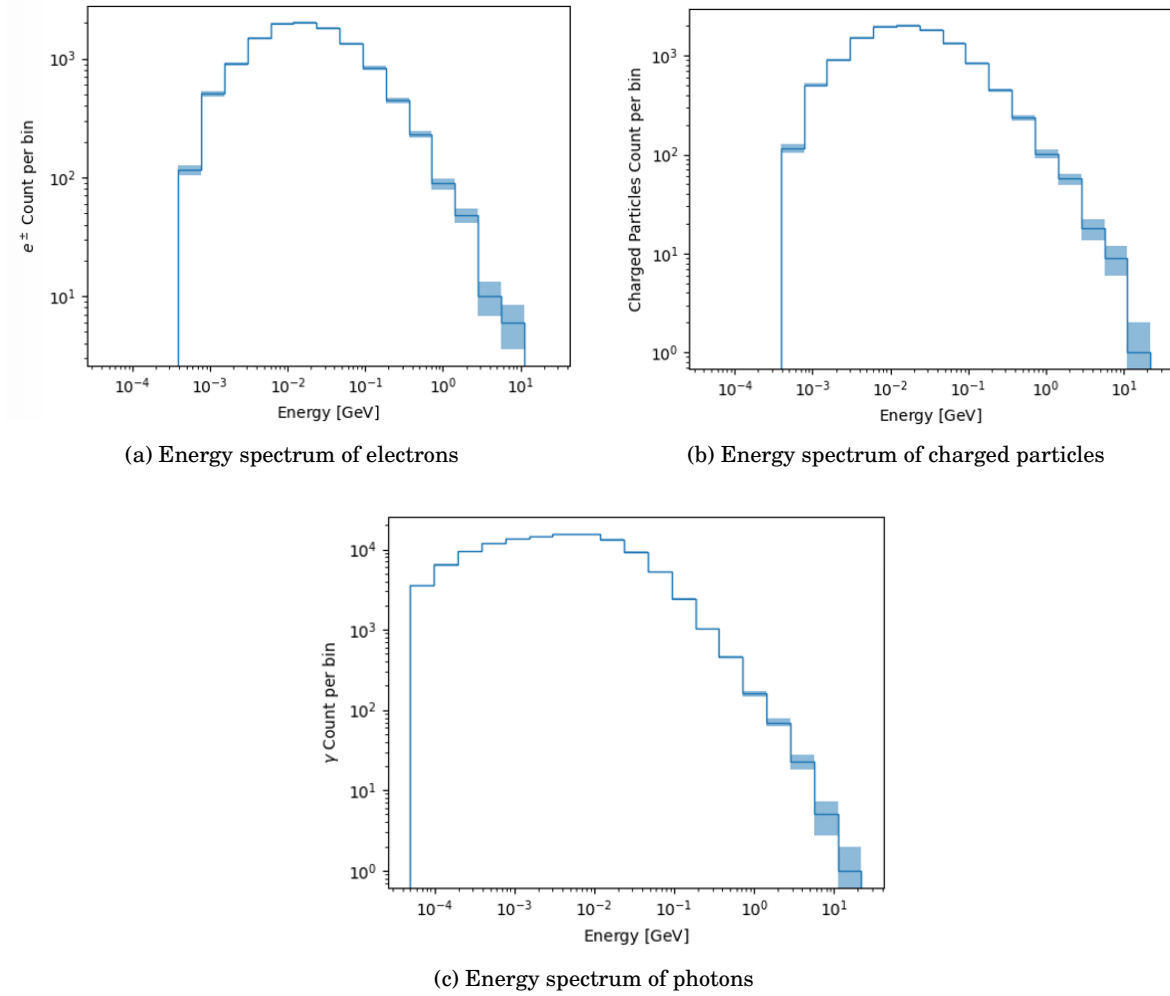


Figure 5.12: Energy spectra of a 10^5 [GeV] primary photon shower.

take a look how the electrons and positrons will behave for the proton (Fig. 5.13 for CONDOR scale and Fig. 5.14 for unscaled).

It can be observed that the production of electrons is much lower compared to that of a primary photon (Fig. 5.5). This can be confirmed in the same way as before, by examining the histogram of the total particle count from the simulation (see Fig. 5.15).

Now, this is very interesting because a greater variety of particles is generated, including protons and pions. However, these are fewer in number, as the photons produced by a gamma ray are on the order of 10^5 , while now, with the cosmic ray, only 10^4 are generated. It seems the same happened with the electrons, but not with the muons, whose generation increased. Just as was done previously, it is also important to observe the behavior of charged particles, as they provide a great deal of information about the cascade in general.

One will note the interesting aspect of this: if Figures 5.13 and 5.16 are compared, it would appear that the charged particles are only electrons and positrons (although other particles can

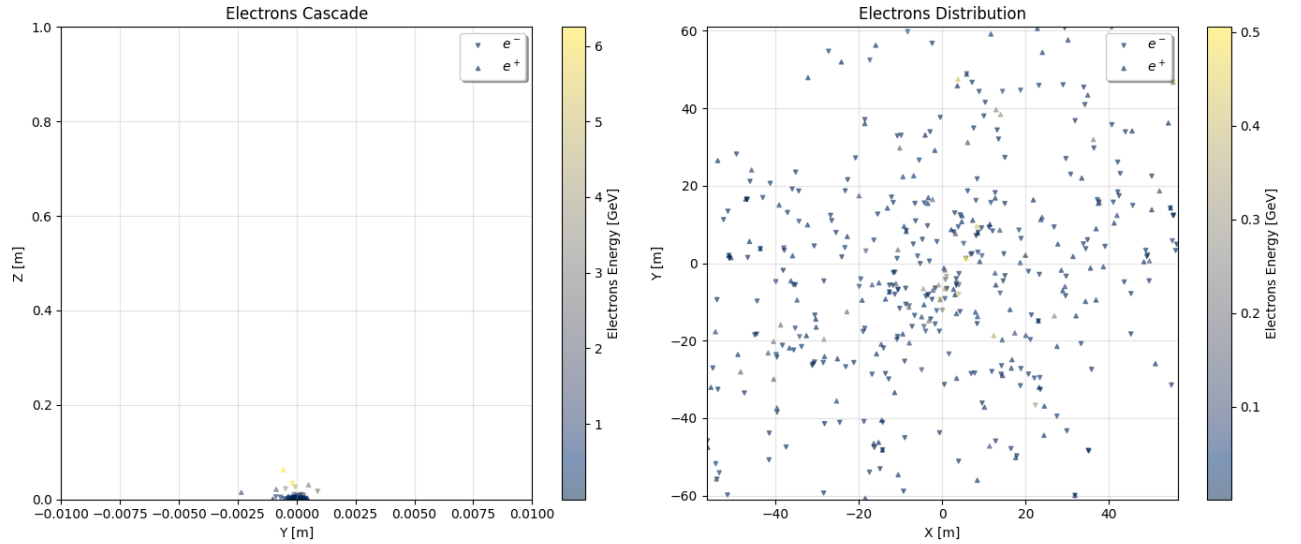


Figure 5.13: Electron and positrons Cascade and Spatial Distribution for a primary proton with 10^5 [GeV] incident energy, also plotted in relation to the detected energy of each electron. Upward triangles correspond to positrons and downward triangles to electrons.

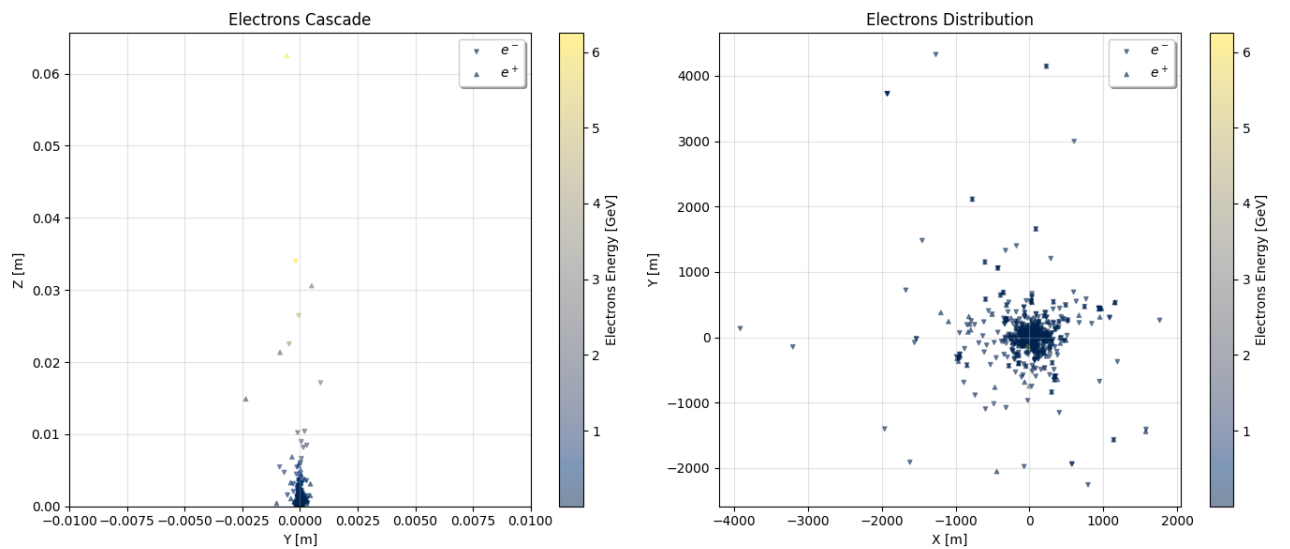


Figure 5.14: Electron and positrons Cascade and Spatial Distribution *unscaled* for a primary proton with 10^5 [GeV] incident energy.

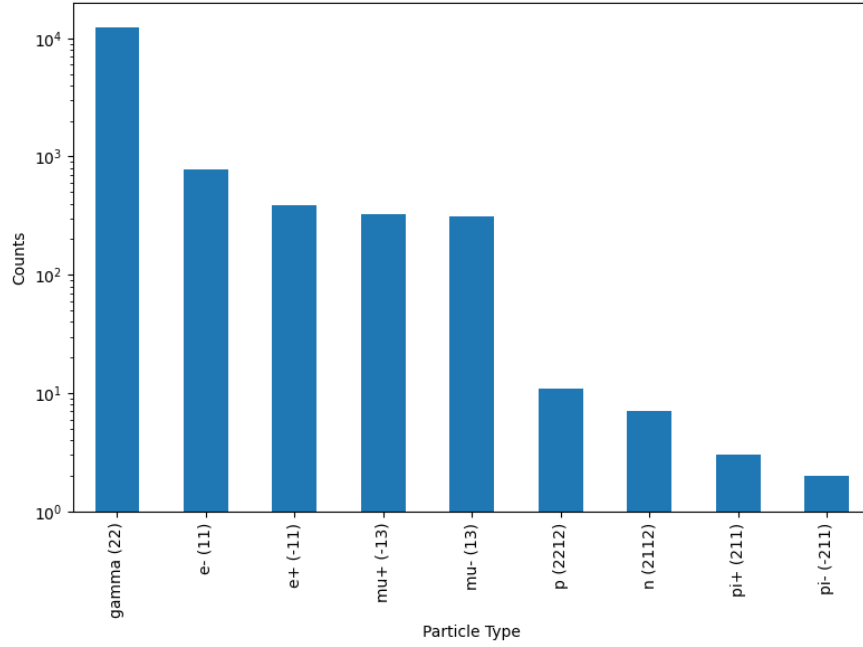


Figure 5.15: Particle count distribution for a primary proton with 10^5 [GeV] incident energy.

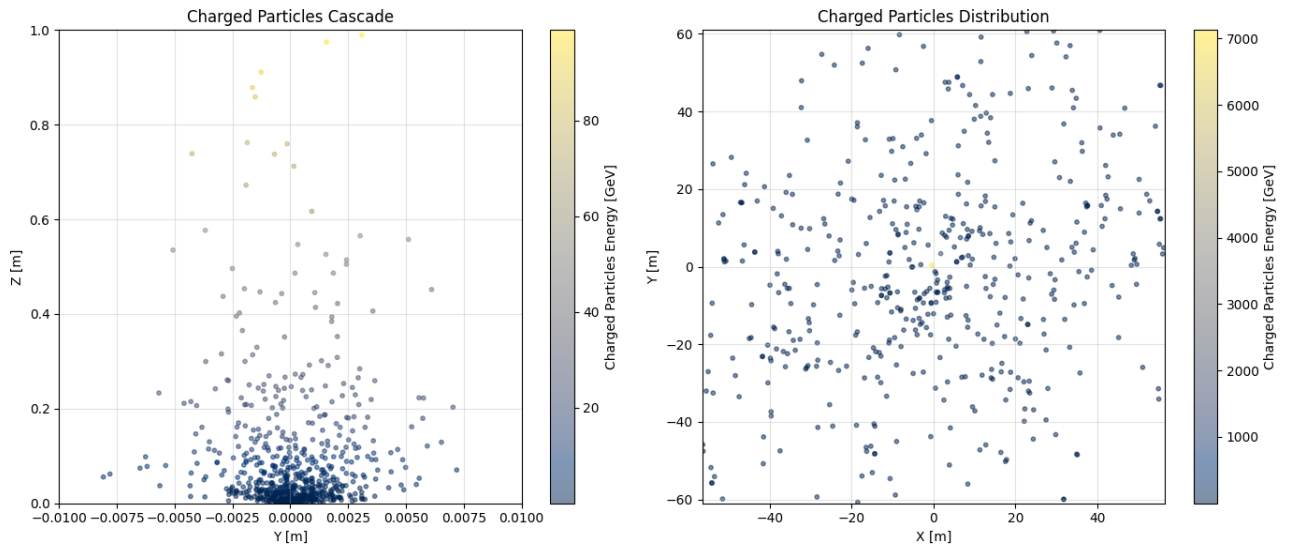


Figure 5.16: Charged particles Cascade and Spatial Distribution for a primary proton with 10^5 [GeV] incident energy.

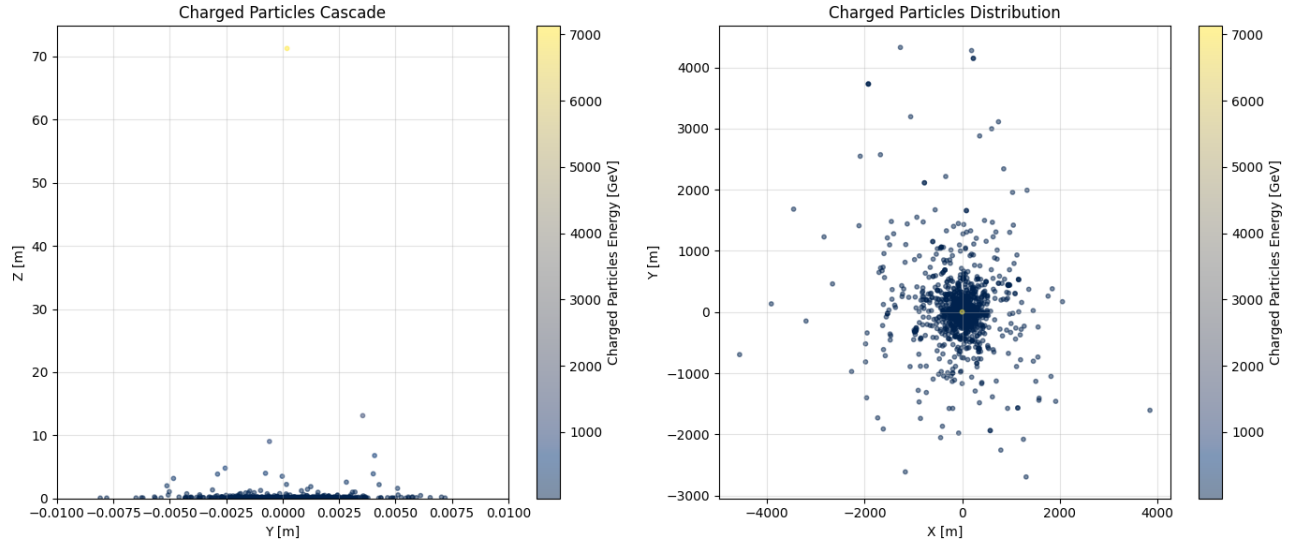


Figure 5.17: Charged particles Cascade and Spatial Distribution *unscaled* for a primary proton with 10^5 [GeV] incident energy.

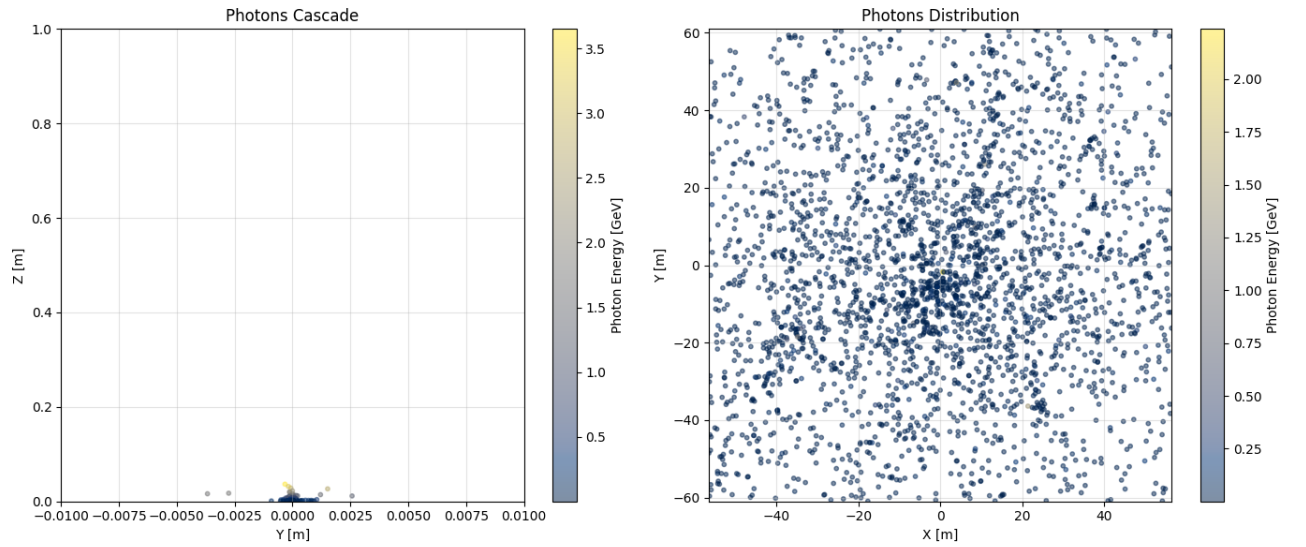


Figure 5.18: Photons Cascade and Spatial Distribution for a primary proton with 10^5 [GeV] incident energy.

be observed). What is happening is that these are the particles formed closer to the center of the cascade, while other charged particles, such as muons, are formed much farther from the center of the cascade, some up to 4000 [m] away (see Fig. 5.17). In contrast, with the incident gamma ray, the charged particles are dispersed only up to approximately 1500 [m] (see Fig. 5.9). However, these are very low-energy particles that do not provide highly relevant information, so the idea that the area covered by CONDOR remains accurate can be maintained.

Finally, just to confirm, the spatial distribution of the photons should be examined, where,

comparing Figures 5.10 and 5.18, the smaller number of these ones can be clearly observed. This can be attributed to the fact that an incident gamma ray tends to produce a greater number of photons due to its high energy interacting with the electromagnetic field, whereas an incident proton, with its different interaction mechanism and energy deposition, generally produces fewer photons [47].

With this, it can be said that CORSIKA 7.7500 enables simulations for gamma and cosmic rays in the GeV-TeV range. It also allows the separation of the behavior of desired particles, enabling the observation of spatial distributions, energy spectra, count histograms, longitudinal profiles, and much more. And, as expected for the measurements from the CONDOR detector array, it can be seen that for a gamma and cosmic rays with 10^5 [GeV] of energy (which is the expected detection range), it is sufficient to detect within an area of 122×113 [m²]. This is because the graphs show that most particles are concentrated in these areas.

5.3 Future work

An exciting prospect for future work is the application of these graphics and simulations in training Machine Learning models [48]. By leveraging the detailed data generated from these simulations, these models can be trained to optimize detection strategies, improve predictive capabilities, and enhance the overall efficiency of observational tasks at the CONDOR Observatory. This integration of advanced computational techniques holds great promise for refining the analysis and interpretation of high-energy astrophysical phenomena that CONDOR wants to study.

CONCLUSIONS

The implementation of CORSIKA 7.7500 has proven to be instrumental in simulating cosmic-ray showers within the GeV-TeV range. These simulations have significantly contributed to the understanding and predictions pertinent to the CONDOR Observatory's studies and future detections.

The analyses of the generated graphics have provided substantial insights. Spatial distributions, energy spectra, count histograms, and longitudinal profiles were meticulously examined, revealing the behavior of primary and secondary particles. Notably, the highest energy particles were photons, although charged particles also exhibited considerable energy levels despite being fewer in quantity.

The ability to simulate various particles and discern their behaviors has been a key achievement. This has facilitated a comprehensive understanding of EAS and the interactions involved, enhancing the accuracy of predictions and the interpretation of observational data.

Moreover, the assessment of the detector array's area, encompassing $122 \times 113 \text{ [m}^2\text{]}$, has validated that this scope is sufficient for detecting the majority of particles (or at least the most important ones), as evidenced by the simulations. This alignment with the anticipated detection range underscores the practical applicability of the simulation results.

In conclusion, CORSIKA has not only enabled detailed and diverse particle simulations but also reinforced the theoretical framework for the CONDOR Observatory. The findings derived from these simulations are expected to guide future observational strategies, contribute to the broader field of high-energy astrophysics, and pave the way for innovative Machine Learning applications in the realm of cosmic ray research.

FLOW DIAGRAM

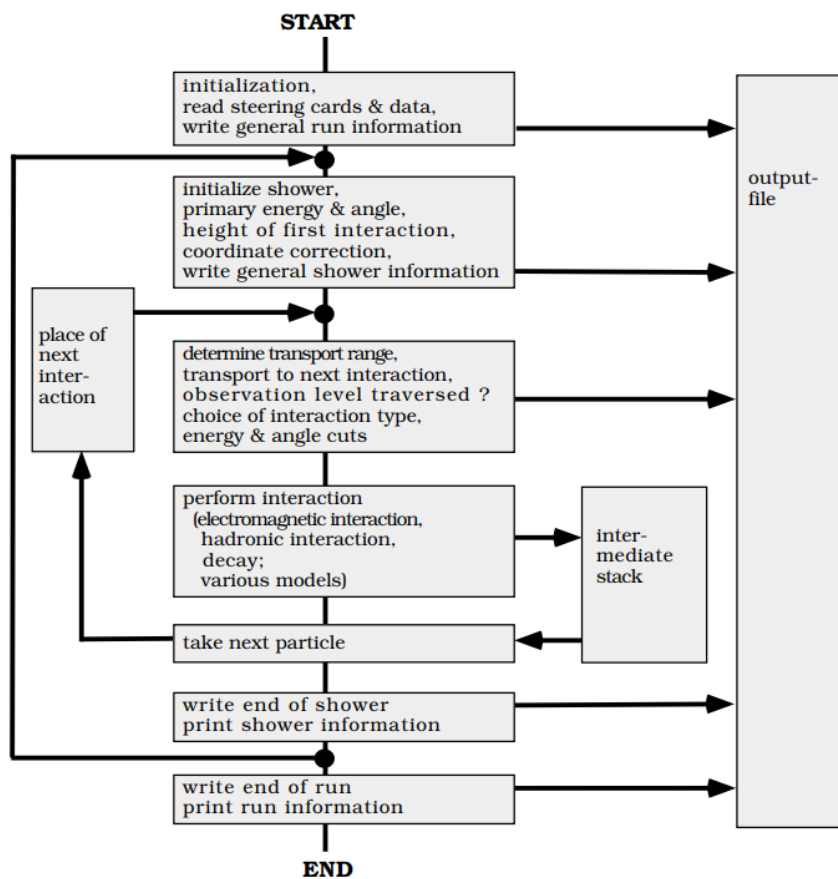


Figure A.1: Simplified flow diagram of CORSIKA [2].

CONDOR TECHNOLOGY

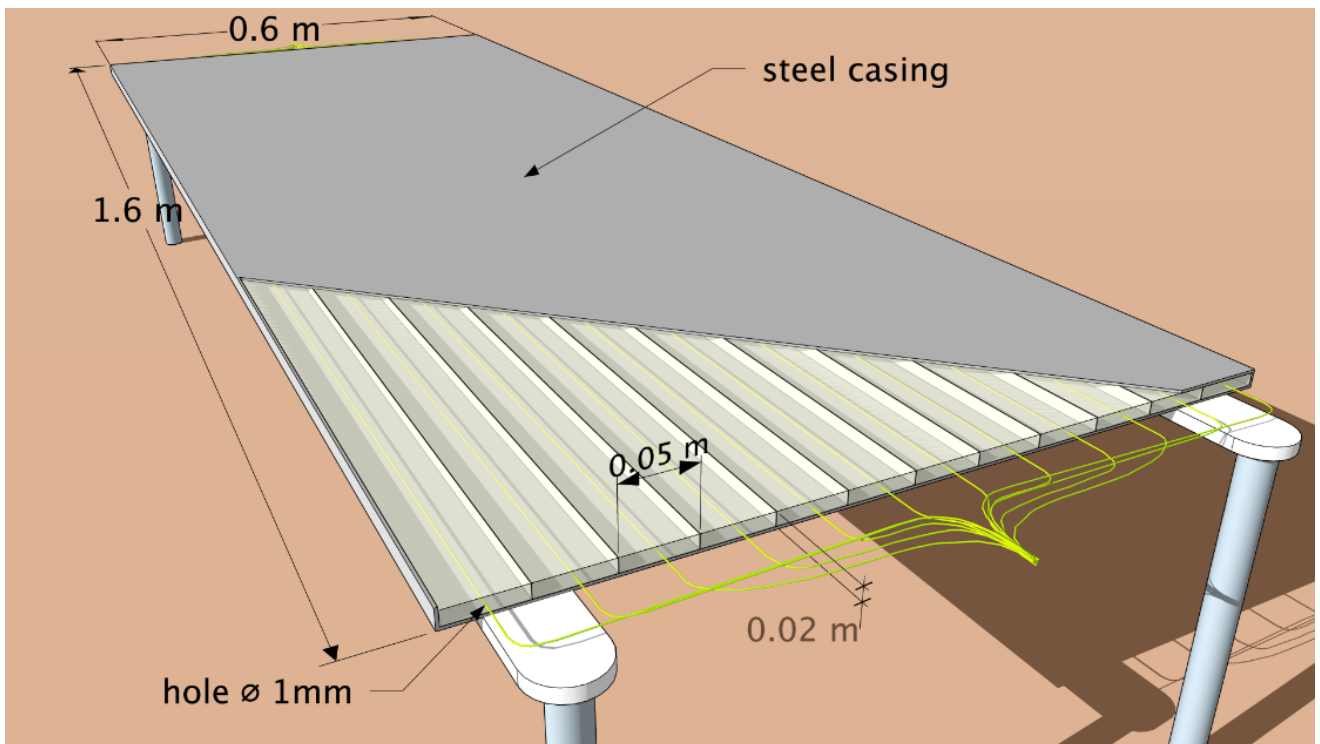


Figure B.1: Schematic layout of a CONDOR detector produced by Fermilab. Source: CONDOR

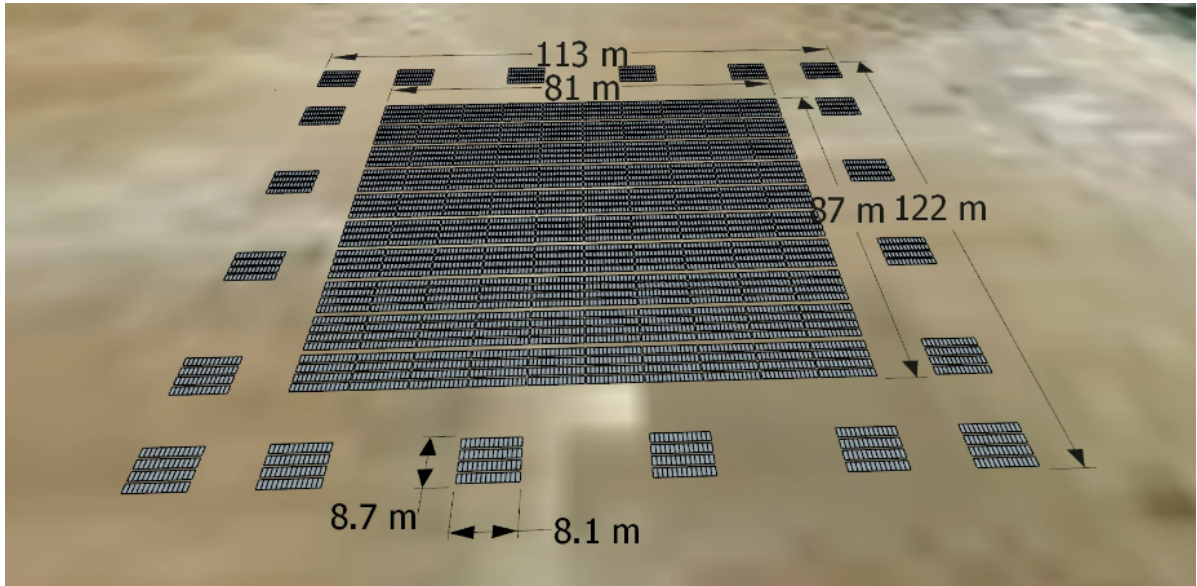


Figure B.2: Schematic layout of the CONDOR detector array. Source: CONDOR

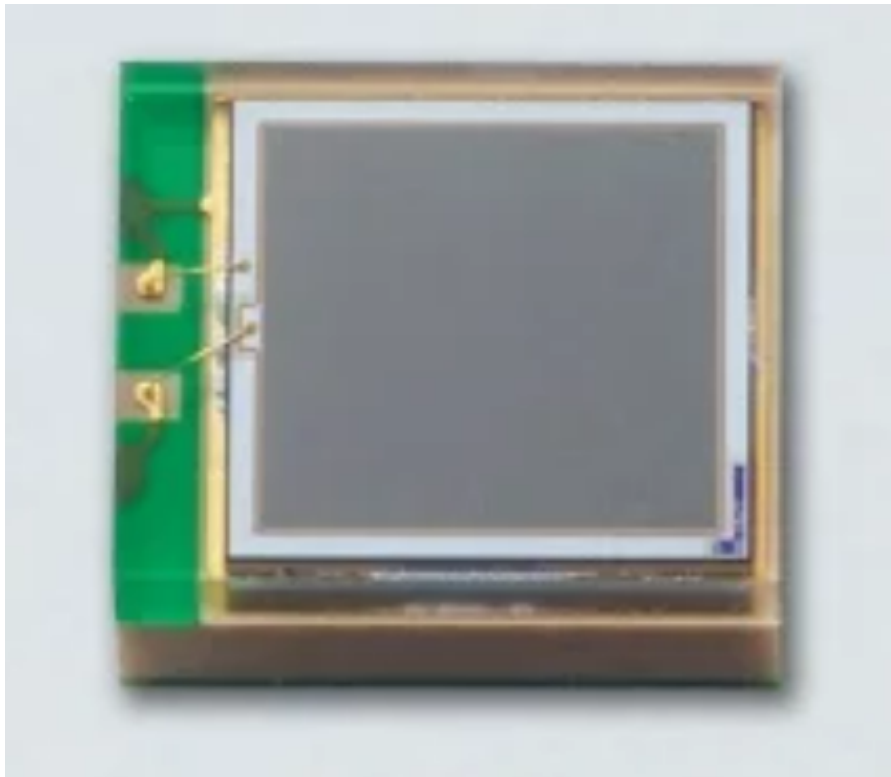


Figure B.3: A silicon photomultiplier (SiPM) used in the CONDOR observatory. Source: CONDOR

VARIABLE ZENITH ANGLE

C.1 15°

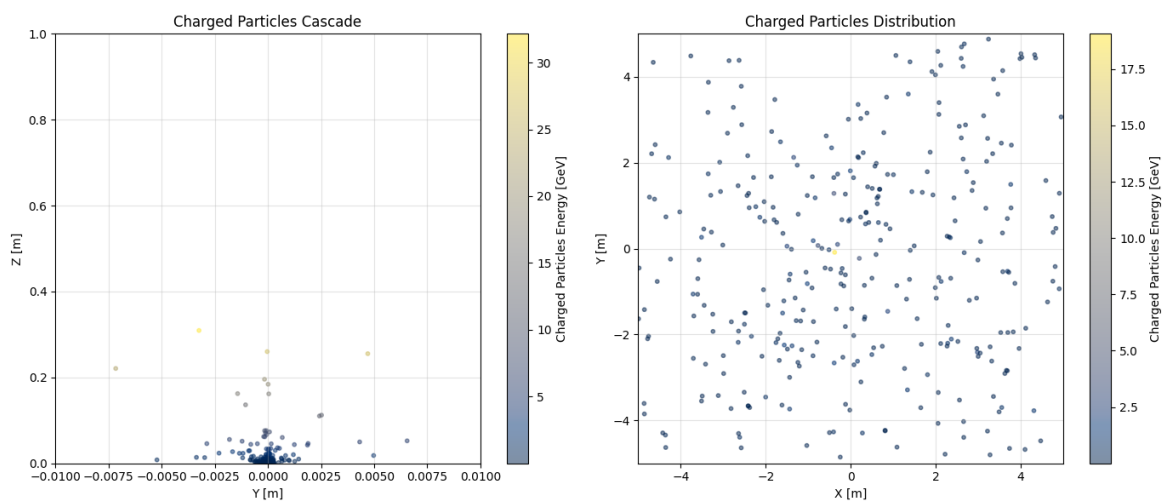


Figure C.1: Charged Particles Cascade and Spatial Distribution for a primary photon with 10^5 [GeV] incident energy and 15° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

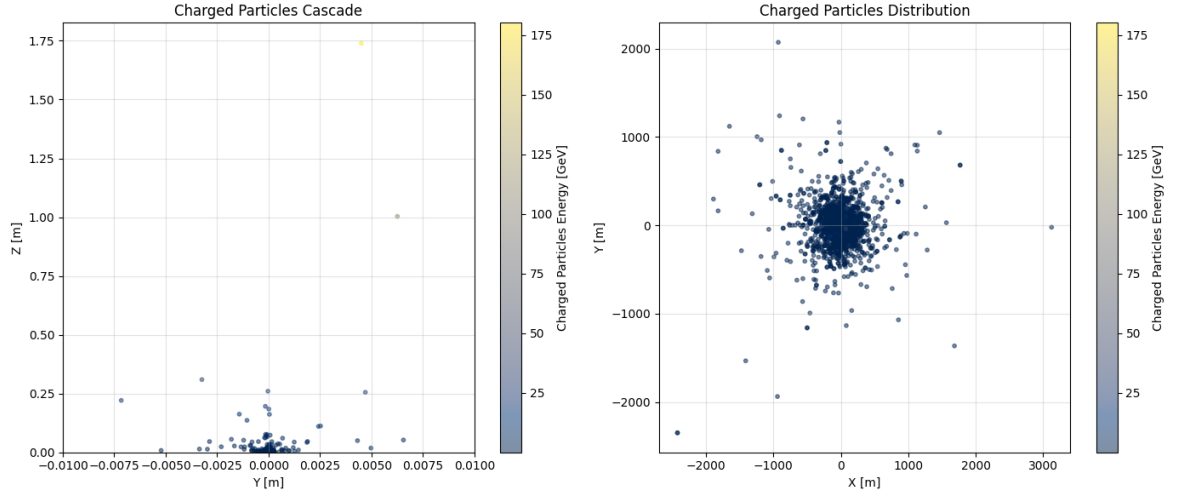


Figure C.2: Charged Particles Cascade and Spatial Distribution *unscaled* for a primary photon with 10^5 [GeV] incident energy and 15° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

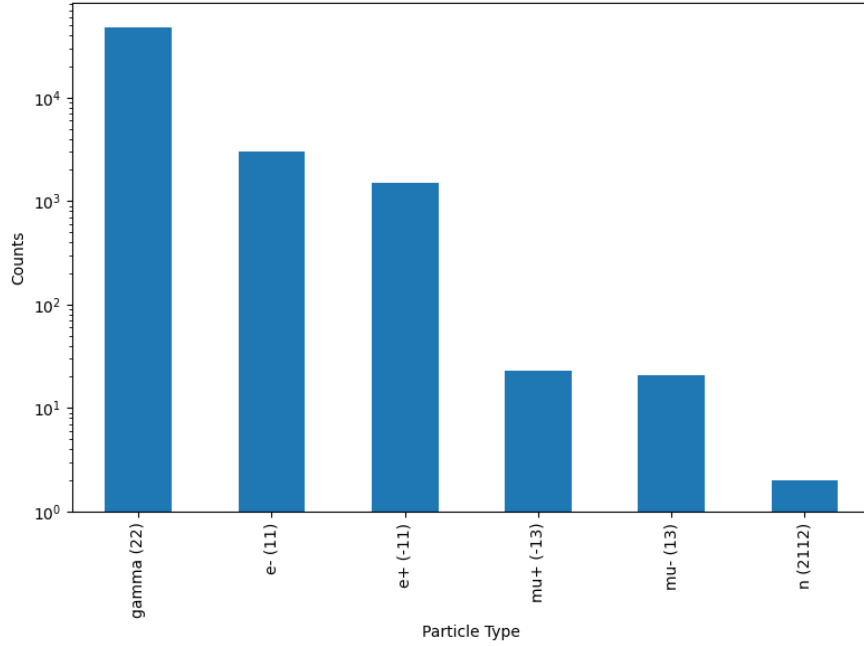


Figure C.3: Particle count distribution for a primary photon with 10^5 [GeV] incident energy and 15° of incident zenith angle.

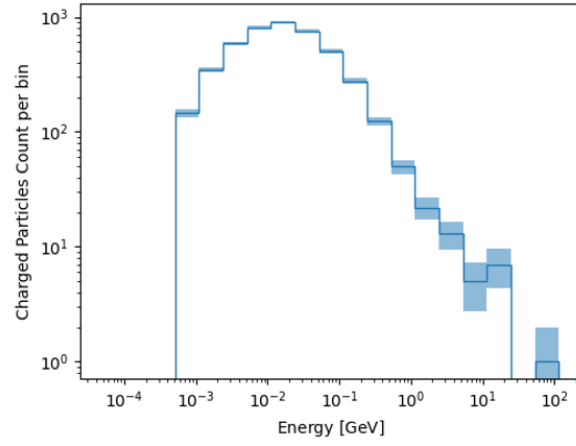


Figure C.4: Energy spectra of a 10^5 [GeV] and 15° of incident zenith angle primary photon shower.

C.2 30°

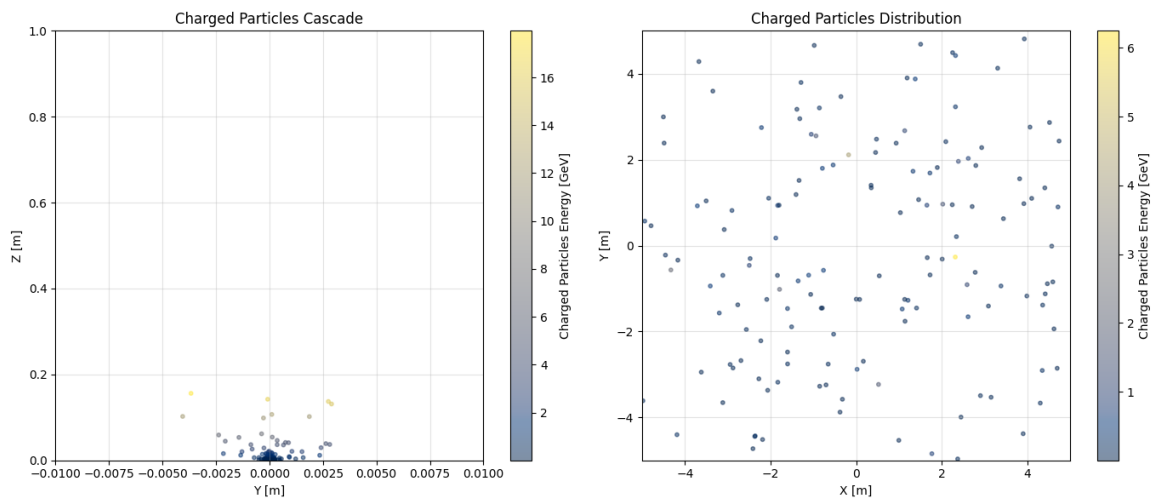


Figure C.5: Charged Particles Cascade and Spatial Distribution for a primary photon with 10^5 [GeV] incident energy and 30° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

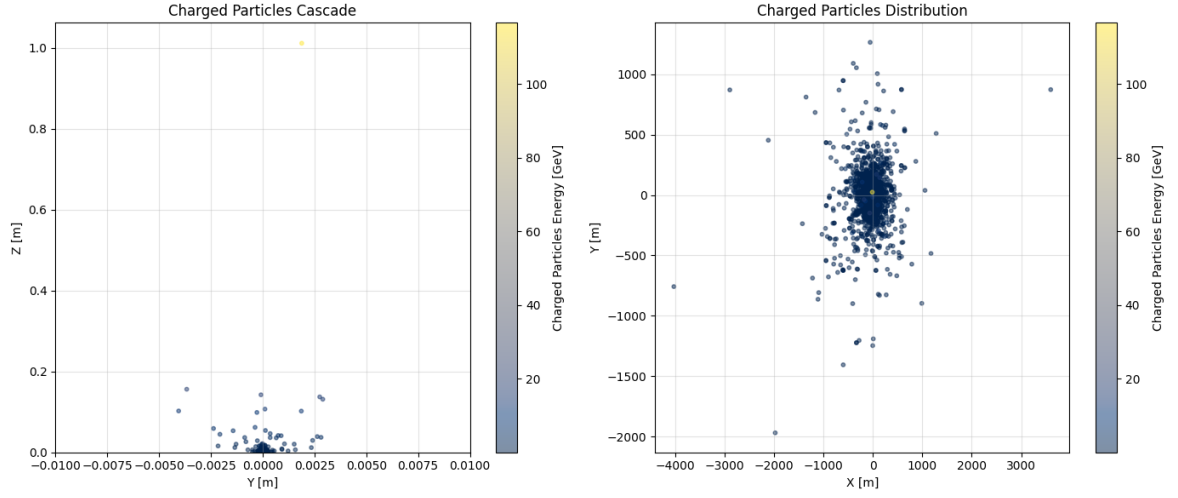


Figure C.6: Charged Particles Cascade and Spatial Distribution *unscaled* for a primary photon with 10^5 [GeV] incident energy and 30° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

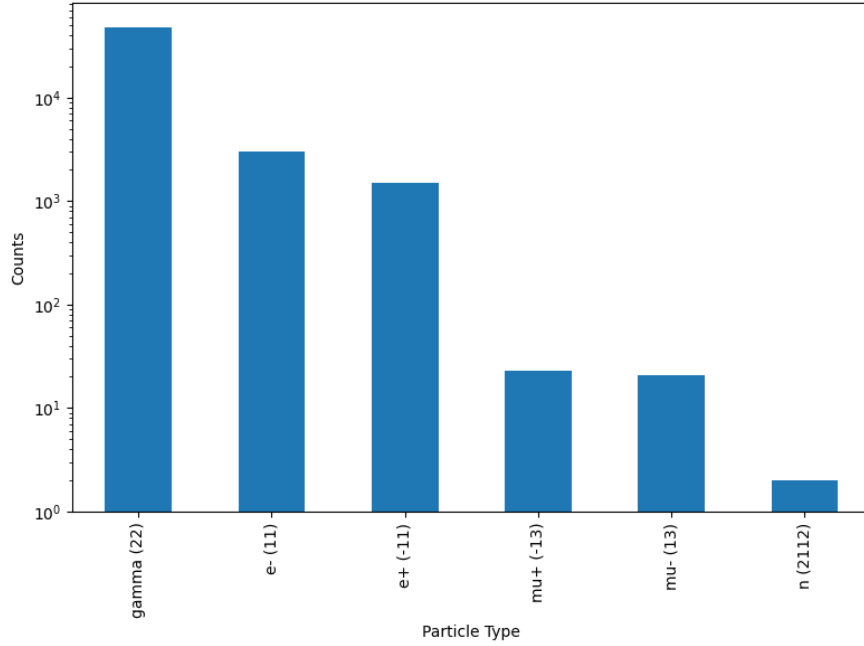


Figure C.7: Particle count distribution for a primary photon with 10^5 [GeV] incident energy and 30° of incident zenith angle.

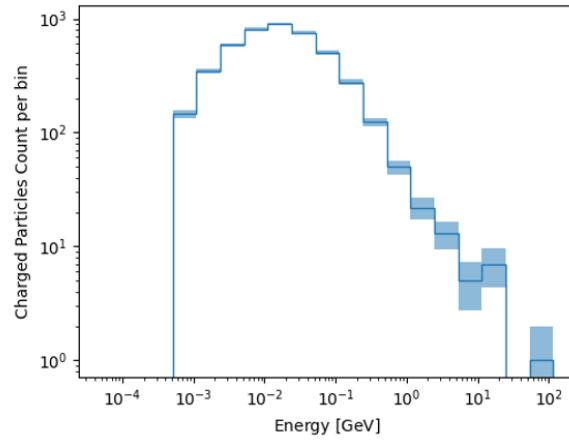


Figure C.8: Energy spectra of a 10^5 [GeV] and 30° zenith angle primary photon shower.

C.3 45°

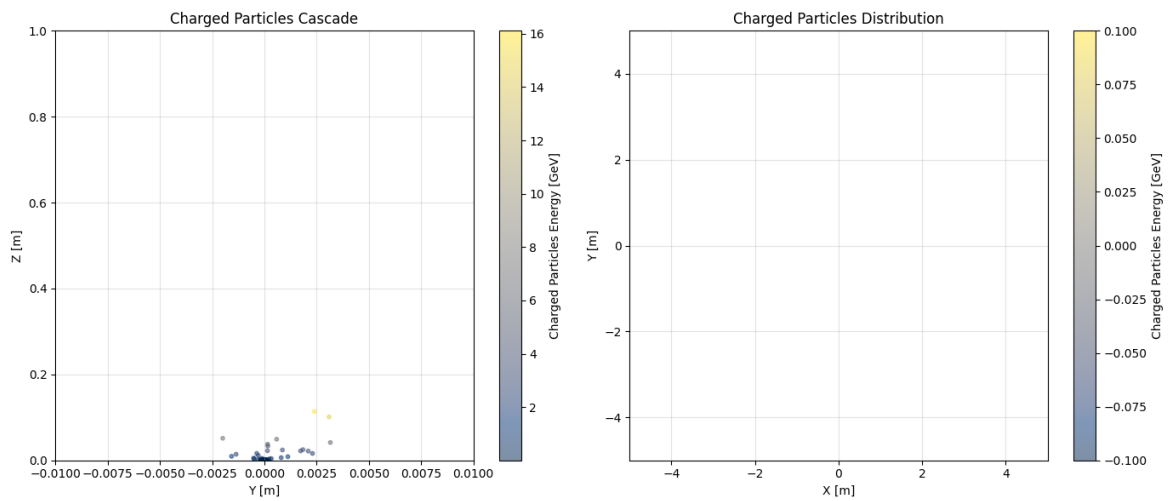


Figure C.9: Charged Particles Cascade and Spatial Distribution for a primary photon with 10^5 [GeV] incident energy and 45° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

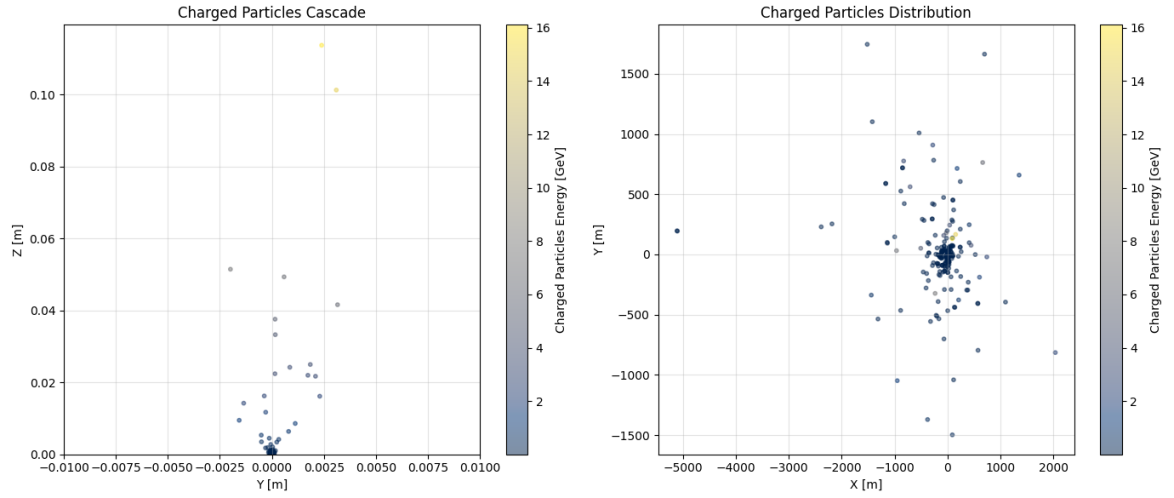


Figure C.10: Charged Particles Cascade and Spatial Distribution *unscaled* for a primary photon with 10^5 [GeV] incident energy and 45° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

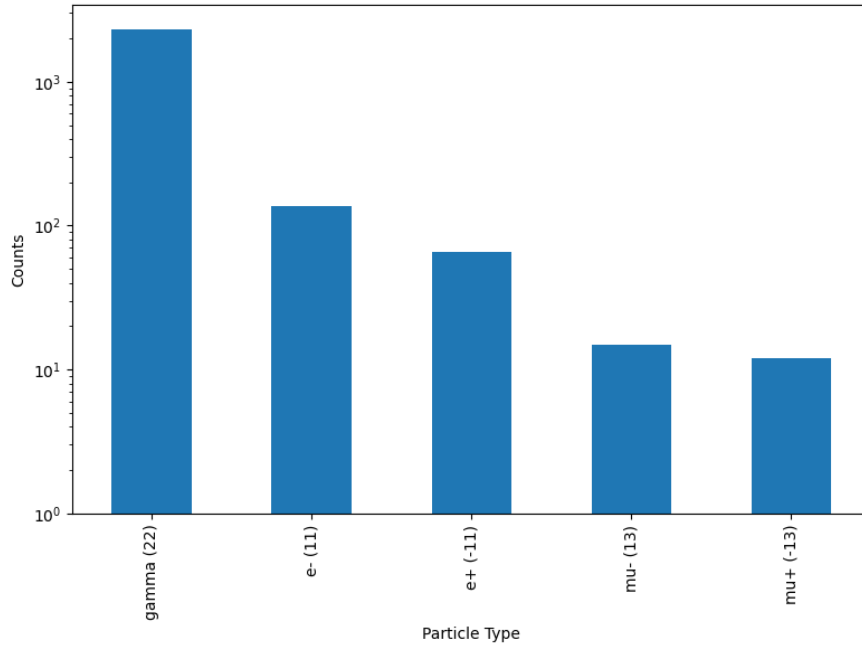


Figure C.11: Particle count distribution for a primary photon with 10^5 [GeV] incident energy and 45° of incident zenith angle.

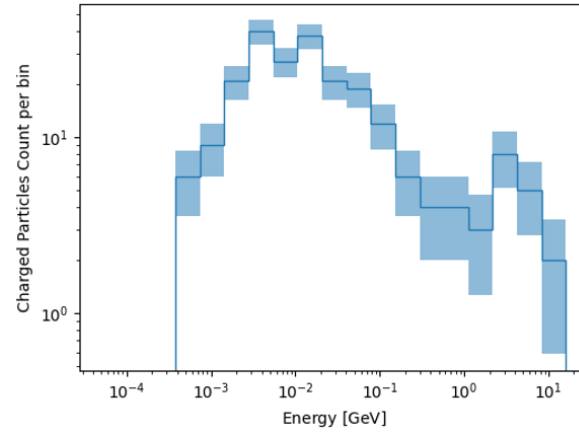


Figure C.12: Energy spectra of a 10^5 [GeV] and 45° zenith angle primary photon shower.

C.4 60°

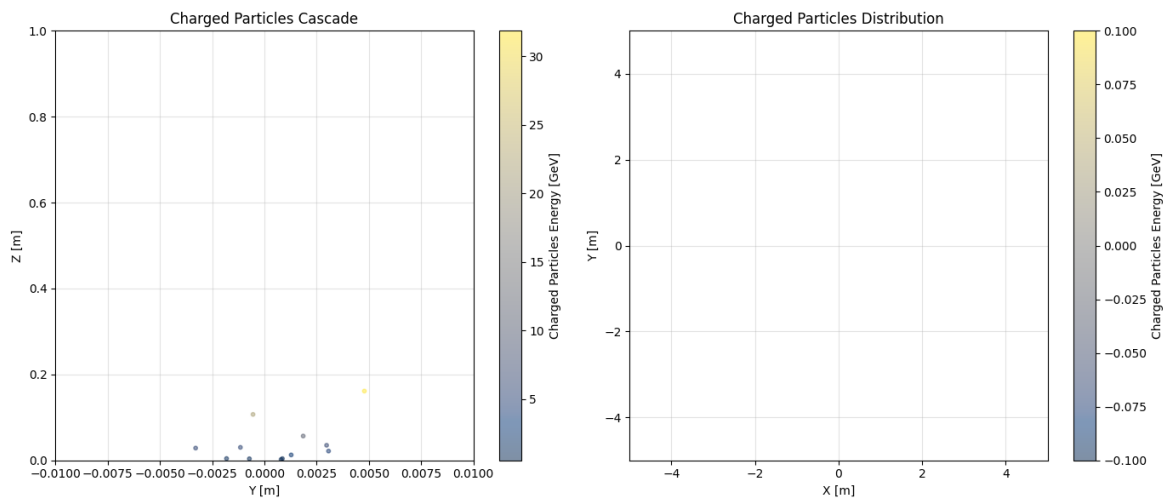


Figure C.13: Charged Particles Cascade and Spatial Distribution for a primary photon with 10^5 [GeV] incident energy and 60° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

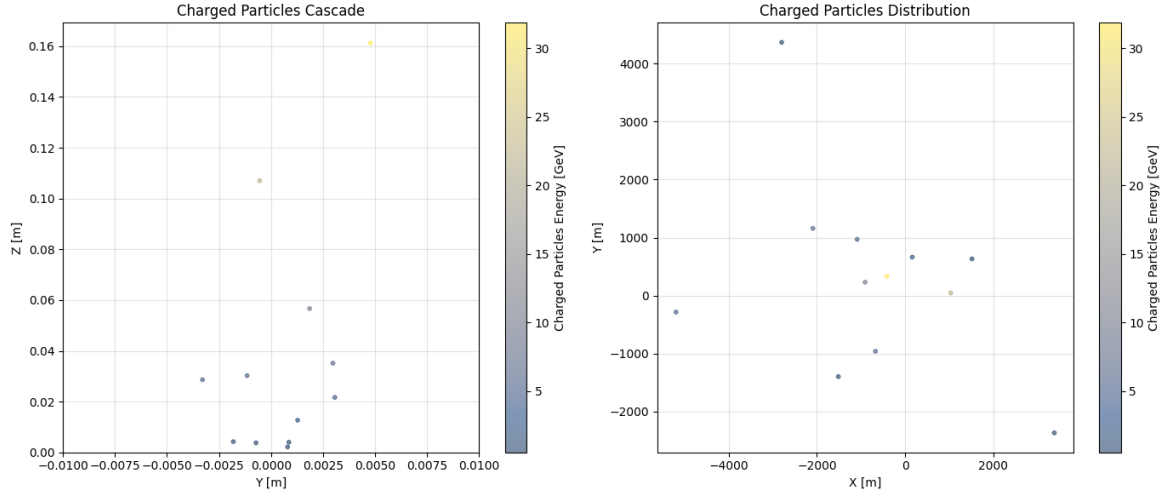


Figure C.14: Charged Particles Cascade and Spatial Distribution *unscaled* for a primary photon with 10^5 [GeV] incident energy and 60° of incident zenith angle. Also plotted in relation to the detected energy of each particle.

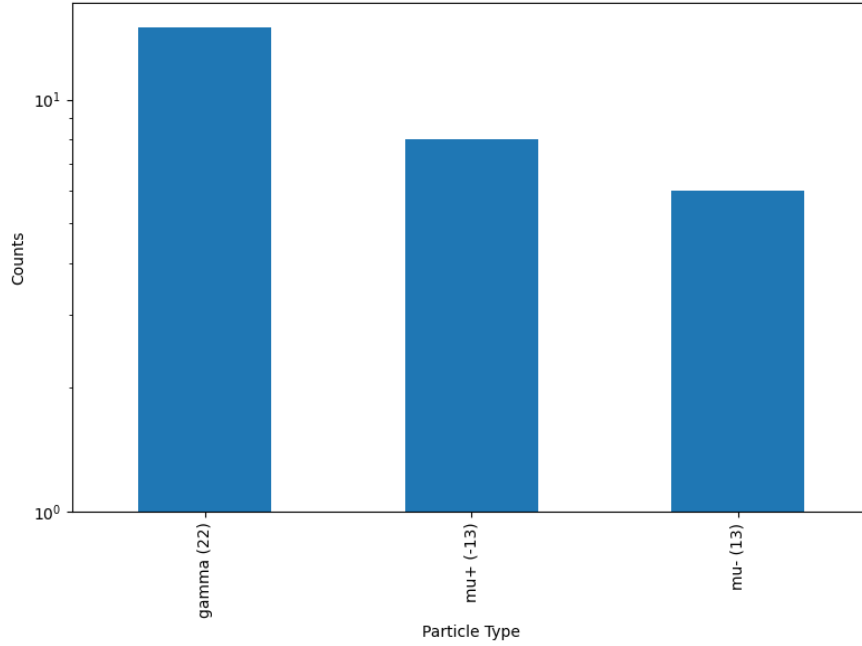


Figure C.15: Particle count distribution for a primary photon with 10^5 [GeV] incident energy and 60° of incident zenith angle.

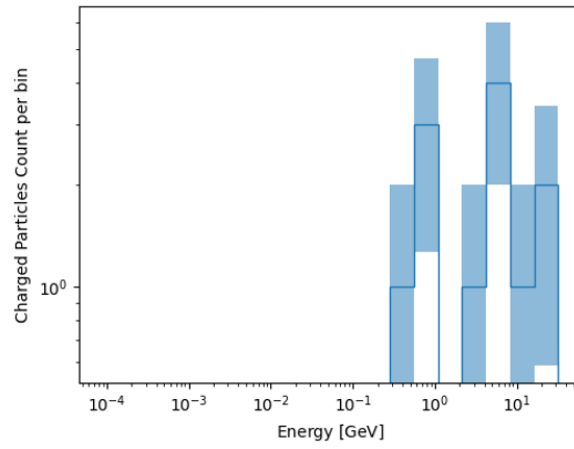


Figure C.16: Energy spectra of a 10^5 [GeV] and 60° zenith angle primary photon shower.

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