UNIVERSITY OF GRONINGEN
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Bachelor Thesis

Characterization of monopole induced air showers using CORSIKA

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Abstract

In this thesis a characterization of air showers induced by magnetic monopoles is presented. Monopoles are predicted to exist and be accelerated to relativistic velocities. High energy monopoles traversing earth's atmosphere continuously deposit energy, inducing an air shower. These air showers have been described based on simulations run in CORSIKA. It was found that monopole air showers are continuous; they plateau after the shower maximum, and have a large electromagnetic component. As such, they can easily be distinguished from normal cosmic rays and most other air shower sources. Very high energy photons and muons could induce similar showers but do not produce identical signals in track-following detectors such as IceCube.

Contents

1 Introduction

"Magnetic monopoles are one of the safest bets one can make about physics not yet seen" according to Polchinski [1]. Any particle having magnetic (yes, *magnetic*, not electric) charge is considered a magnetic monopole. Indeed, he is not alone in concluding that given our theoretical knowledge, magnetic monopoles (MMs, or just monopoles) might very well exist. Monopoles are hinted at or outright predicted by different areas of physics, as discussed in the theoretical section.

Apart from their hypothesized existence, they are also predicted to fly through the cosmos at relativistic speeds, potentially reaching earth. If so, it is a natural conclusion that monopoles will create air showers in the earth's atmosphere not unlike other air showers that have been observed.

Air showers are initiated when a very high energy particle collides with mass, in this case an atmospheric atom. The large energies involved cause the atom and or the incident particle to split up or produce other particles. This process repeats itself for the new particles creating another generation. The whole process results in a 'shower' potentially containing billions of particles. In figure 1 the flux of cosmic rays—the most abundant air shower producing particles—is plotted over the energy range. The higher the energy of the incoming particle, the smaller the flux.

Figure 1: Observed cosmic ray flux as a function of particle energy

In this research, an attempt is made to answer the following question: what are the characteristics of a monopole induced air-shower in, surface arrays, specifically IceTop; other detectors, like IceCube? Answering this question clears the way for the first detection of a magnetic monopole. If one is observed, many unanswered questions will finally be resolved, and undoubtedly this would mark a huge step forward in many different fields both within and outside of physics.

In order to characterize monopole induced air showers, our *a priori* knowledge of monopoles is used to make simulations for monopoles with energies ranging from 10^{10} GeV to 10^{15} GeV. These simulations are performed by the CORSIKA software package, and compared to simulations of other potential air shower producing particles. Protons, iron nucleii, muons and photons are also studied here as reference material for monopole showers. Energies from 10^5 GeV to 10^{10} GeV are studied for cosmic rays. As can be seen in figure 1, this corresponds to the very right end of the spectrum. As such this study focuses on the highest
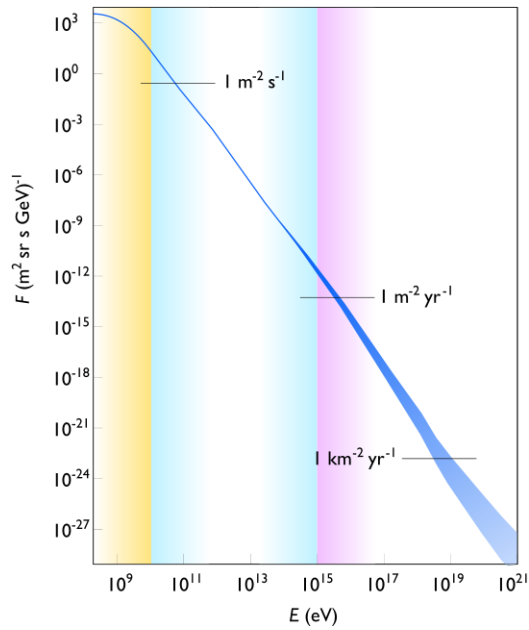
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energy air showers.

Following this introduction section 2 will treat all the relevant theoretical aspects of magnetic monopoles. In section 3, the IceCube observatory will briefly be discussed. Section 4 discusses the software used for the simulations. In section 5 we will look into the approach used to characterize the monopole showers, before moving on to section 6 where the results are discussed. Finally the research is concluded with a positive look to the future.

2 Theory

Magnetism is a concept that has been around for a very long time. Magnets and magnetic materials attracted the interests of the ancient Greeks, and were already used as a tool of navigation a thousand years ago [2]. Today, it is impossible to imagine the modern world without the possibilities of magnets. Think of the frontiers of research such as the Large Hadron Collider with its super conducting magnets, but also of the simpler things; compasses, speakers and phones would not work without them.

In all the aforementioned examples we are talking about magnetic dipoles. These are magnets that have two poles with opposite polarity, a north and a south pole. It is common knowledge that two like poles repel each other, and two unlike ones attract. One might expect that if a dipole is cut in two, one would end up with a separate north and south pole. Instead two smaller dipoles appear. In fact, these individual poles—monopoles—have never been observed.

The important difference between a magnetic monopole and a magnetic dipole is that the monopole must have a magnetic charge. Magnetic charge behaves similar to electric charge in some ways, but is fundamentally different, as explained in section 2.2. A magnetic dipole does not have this condition. The two poles of a dipole are created by the periodic motion of electric charge and do therefore not imply the existence of magnetic charge.

2.1 Predictions of magnetic monopoles

Perhaps the most common prediction of magnetic monopoles is through Maxwell's equations. In the middle of the nineteenth century, James Maxwell formulated four formulas that tie together electricity and magnetism very neatly [3]. Normally—i.e. in the absence of MMs—they read,

$$\nabla \cdot \mathbf{E} = 4\pi \rho_e \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e \tag{4}$$

where $\mathbf{E}$ and $\mathbf{B}$ are the electric and the magnetic field, respectively. ρ_e is the electric charge density and $\mathbf{j}_e$ is the electric current density. All equations are

given in Gaussian units. Equation (3) gives the electric field generated by changes in the magnetic field, equation (4) the magnetic field generated by a changing electric field. Equation (1) determines the electric field in the presence of an electric charge. Equation (2) is naturally zero, as Maxwell never intended for his equations to account for MMs; he did not think they exist.

Let us now incorporate the notion of MMs in the equations. Equation (2) changes to

$$\nabla \cdot \mathbf{B} = 4\pi \rho_m, \tag{5}$$

where ρ_m is the magnetic charge density[4]. Equation (3) becomes:

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} - \frac{4\pi}{c}\mathbf{j}_m, \tag{6}$$

where $\mathbf{j}_m$ is the magnetic current. It is evident that this leads to a more symmetric form of the equations. Indeed, Maxwell's four equations are invariant under an inversion of $\mathbf{E}$ and $\mathbf{B}$.

$$\mathbf{E},\ \mathbf{j}_e,\ \rho_e \to \mathbf{B},\ \mathbf{j}_m,\ \rho_m \qquad\qquad \mathbf{B},\ \mathbf{j}_m,\ \rho_m \to -(\mathbf{E},\ \mathbf{j}_e,\ \rho_e) \tag{7}$$

It is this simplicity and symmetry that often convinces a physicist of one theory rather than another, if there is reason to believe in both. Nature is complex, but hardly ever more complex than it needs to be. That is why the aesthetics and simplicity of a symmetric set of Maxwell's equations are convincing arguments for the existence of magnetic monopoles.

Another theoretical argument for the presence of MMs is the *Dirac quantization condition* [2][5]. Paul Dirac made a notable discovery while trying to formulate a magnetic monopole in quantum theory. He found that under the assumption that monopoles exist,

$$\frac{g \cdot q}{2\pi} \in \mathbb{Z} \tag{8}$$

where $\mathbb{Z}$ is the set of all integer numbers. What this condition shows is that assuming magnetic charge exists, electric charge is quantized. In other words, electrically charged particles are not allowed to take just any value, only discrete values are allowed.

It is well known that all charged objects that have ever been observed have a quantized charge of multiples of $e/3$, where e is the elementary charge. So far a clear answer to why all electrical charge is quantized has not been found. The existence of magnetic charge and with it the Dirac quantization condition would give a clear explanation. However, even if charge quantization is explained differently, it has been argued that all theories predicting a quantization of electric charge inevitably predict the existence of (quantized) MMs as well [1].

Diracs quantization condition leaves little room for the physical world to both statisfy this condition and exclude monopoles from reality. Furthermore, an investigation into the physical models prevalent today confirms this impression. Any theory combining the three best understood fundamental interactions — the electro-magnetic, the weak and the strong interactions or a Grand Unified Theory (GUT)— is bound to predict 't Hooft-Polyakov monopoles, a certain kind

of monopole predicted to exist on topological grounds [6]. That is, if one has any hopes of understanding the world in terms of a general theory, even excluding gravity, one will have to settle for magnetic monopoles as well.

There are many arguments to be made for the existence of monopoles, of which only a few have been considered here. Conversely, arguments to the contrary are absent, except for one. A magnetic monopole has never been observed. Yet this is no reason to stop looking for them, or not to prepare for the possibility that we will observe one in the future. For a more elaborate review of predictions of monopoles, see [2]. For an extensive account of theory regarding monopoles, see [4].

2.2 Cosmic monopoles: energy and mass

It is not clear what a monopole looks like save the fact that it has magnetic charge. For example, the mass is not known, even though this is a crucial characteristic. A crude estimation of the possible mass range can be made, based on theoretical arguments and experimental data. Some conclusions regarding their creation and energy while traversing the universe can also be reached.

Monopoles are expected to have been produced during symmetry breaking in the early universe. Once the universe developed further and monopole production stopped, the result was a constant, isotropic monopole flux that could only decrease through decay. These monopoles are absolutely stable [2] and therefore an observable flux is expected.

Since the universe settled down to the structure we see today, large formations generate magnetic fields through many different processes. Analogous to electric charges in an electric field, monopoles will be accelerated in these magnetic fields. Particularly galaxy clusters and extragalactic sheets have the potential to accelerate monopoles to ultra-relativistic speeds, with energies of up to 10^{16} GeV [7]. Unfortunately, accounts of the monopole mass are much more uncertain.

The lower bound of the monopole mass is based on two arguments. At the Large Hadron Collider at CERN, collisional energies have been reached of several TeV. When a monopole has a mass below half this value, it should be produced during some of the collisions. In this case we would expect to have found it already. Accordingly, characterising monopoles below 1 TeV is ill-considered.

Secondly, the production of monopoles in the very early universe during the phase transitions is predicted to happen at a mass starting from 10^3 GeV/c^2 up to as much as 10^{17} GeV/c^2 for the first phase transition [8]. Specifically, monopoles below a mass of $4 * 10^4$ GeV/c^2 are considered to violate the Standard Model of physics.

Monopoles of a much higher mass would be orbiting massive objects such as galaxies or stars with nonrelativistic velocities [6]. Only below a mass of 10^{14} GeV/c^2 are monopoles expected to be accalerated to relativistic velocities by (extra-)gallactic magnetic fields [7]. Nonrelativistic monopoles will not create air showers of the kind that is focussed on in this research.

A more practical consideration is the mass investigated by the Pierre Auger Collaboration in their paper 'Search for ultrarelativistic magnetic monopoles with

the Pierre Auger observatory', which we follow to some extent [8]. Ultrarelitivistic monopoles with a mass in the range 10^4 GeV/c^2–10^8 GeV/c^2 are studied by the collaboration.

Taking everything in consideration, the decision has been made to investigate aair showers induced along the path of a relativistic monopoles with a mass of 10^5 GeV/c^2. A single value has been taken rather than a range for simplicity as well as efficiency. Since the development and energy deposit of a monopole induced aair shower depends on the Lorentz factor gamma rather than the mass [7][8], the results will not lessen in generality.

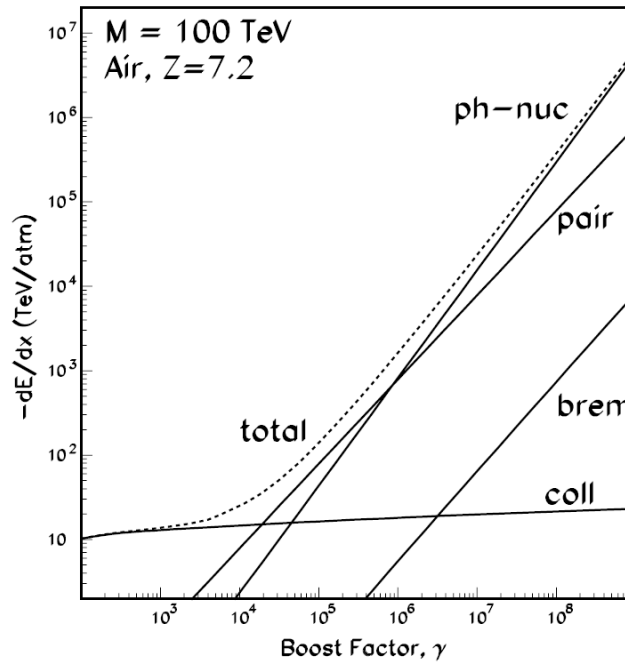## 2.3   Monopole energy loss through matter

Figure 2: Contributions to monopole energy loss at different speeds, from [7]

In addition to the existence, stability and acceleration of monopoles, the search for atmospheric monopole showers rests on one more assumption: the ability to produce an air shower. Wick *et al.* have determined a reliable electromagnetically-induced signature of a monopole. A continuous, compact aair shower is predicted from a relativistic monopole traversing the earth's atmosphere. This continuous shower production is due to the electromagnetic interaction only and therefore very similar to a muonic track. The hadronically-induced signature is not understood as well, and therefore highly model-dependent. However, the electromagnetic part of the shower is sufficient since it is accurately measured by IceCube and IceTop.

As a consequence of the electromagnetic interaction, monopoles lose energy through all the processes that make other primaries lose energy: bremsstrahlung; collisional enery losses; $e^+ e^-$ pair production; the photonuclear effect. Bremsstrahlung

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is emitted when charged particles are decelerated in matter. The amount of energy radiated roughly scales with the inverse of the mass, and is therefore negligible for the intermediate mass monopoles studied here. Collisional energy losses cover ionization and excitation of electrons in the traversed medium. Pair production is understood as the combined production of any particle and its antiparticle together. Finally, the photonuclear effect is the exchange of a virtual photon between the monopole and an atmospheric nucleus. This effect is responsible for the majority of energy loss at high energies, i.e. $\gamma > 10^6$, as seen in figure 2.

3 IceCube and IceTop

The IceCube Neutrino Observatory is located at the geographic South Pole. Fully operational since 2011, it has been designed for measuring very high energy neutrinos. However, experiments have been performed concerning muons, cosmic rays and other physics [10]. The observatory consists of two components, IceCube and Ice-Top.

IceTop is an array of 81 tanks filled with clear ice, located on the surface of the South Pole. The spacing between the tanks is 125 meters, spread out over approximately 1km^2. Two digital optical modules, or DOMs, are present in each tank. The DOMs amplify and detect any light signal produced in the tank. Whenever a relativistic charged particle travels through the ice in the tank it leaves a trail of Cherenkov radiation, light emitted when a particle moves trough a dielectric medium

Figure 3: IceCube schematic from [9]

faster than light does. It is this light that is measured by the tanks of Ice-Top. Consequently, IceTop excels at measuring electrons and positrons ($e^\pm$) and (anti-)muons ($\mu^\pm$), as these are the most abundant charged particles in most air showers at observation level. Tauons could in principle be measured as well, but tend to decay very quickly. For an elaborate review of IceTop and its characteristics, see [11]

Directly beneath IceTop the main detector is located. IceCube consists of 86 strings deep into the clear ice of the South Pole, reaching down to a depth of 2450 meter. Each string is outfitted with similar DOMs as in the IceTop array, starting from a depth of 1450 meter, totaling an instrumented length of one kilometer. As it covers the same area that IceTop does, about 1 km^3 of ice is continuously
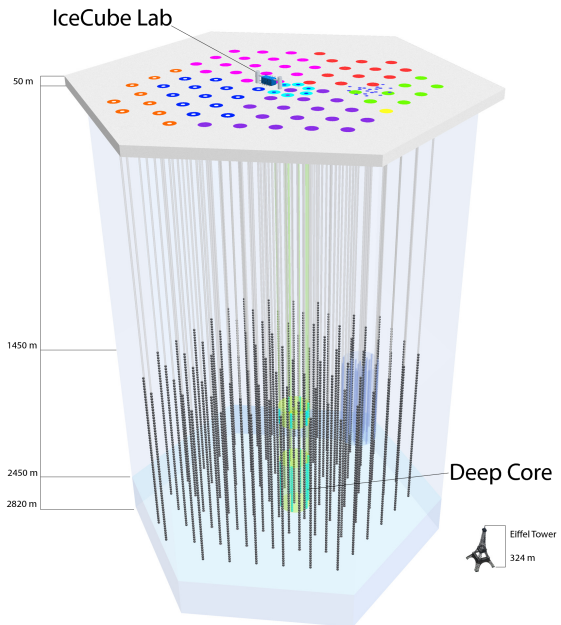
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monitored for Cherenkov radiation. Contrary to IceTop—capable of measuring at just one observation height—IceCube has the ability to follow a particle shower along the shower axis and reveal the longitudinal shower development. The in-ice array is placed under a layer of ice 1500 meters thick to shield it from unwanted background. In practice, muons of a high enough energy to reach through 1500 meters of ice constitute the only signal of an air shower for IceCube. The rest of the shower content has scattered or decayed by then. IceTop was devised to veto events that are detected, given the initial focus on up-going events rather than down-going.

Recently, tools have been designed by the IceCube Collaboration that increase the functionality of IceTop past vetoing events for IceCube. For one, data of the whole IceCube observatory has been used to determine the lateral distribution of muons in an air shower as a function of the primary energy. With this distribution, an accurate energy spectrum of incoming cosmic rays has been made [9]. Similarly, an effort is being made to use the lateral distributions of both $e^\pm$ and $\mu^\pm$. The relative strengths of the two signals then determine the mass of the primary particle [12]. At this time this has been accomplished over the average of many showers, but reconstructions are being developed that will be able to distinguish the primaries for individual events. When these tools are finished and in use, it is in principle possible to identify a monopole induced shower through a characteristic em and muon signal in IceTop.

These new tools for IceTop all depend on its ability to distinguish an $e^\pm$ from a $\mu^\pm$. The tanks on the surface measure an amount of light from an incident particle that is largely dependent on the distance traveled through the tank. Since electrons and positrons easily scatter, it is unlikely that they travel through the whole tank. Typically, they scatter and decelerate below the Cherenkov threshold quickly. This is in contrast with a much heavier muon, that tends to travel through the whole tank. As a result, an incident $\mu^\pm$ produces a much larger light signal than an $e^\pm$.
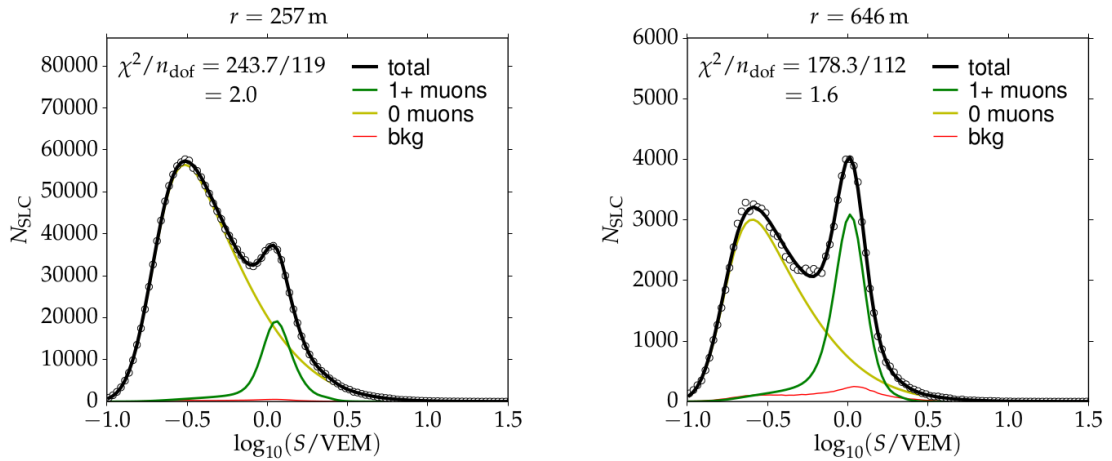

Figure 4: Muonic (light green) and electromagnetic (dark green) signal in IceTop at 257m and 646m from shower centre

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In figure 4 two separate peaks can be seen: the first corresponding to the signal produced by electrons or positrons, the second to the signal produced by muons. In the second graph of tanks farther away from the shower center, the second peak is more prominent. Muons reach outward more easily because they do not scatter as much, thus leading the signal at large distances from the shower axis, r. It is the proportion of these two peaks as a function of r that allows IceTop to determine the type of the primary particle.

4   The CORSIKA software package

All airshowers investigated here were simulated using the CORSIKA software package [13]. CORSIKA was developed some twenty years ago for the KASCADE experiment in Germany. In the twenty years that followed it has been adapted and improved continuously. Although it is not the only program developed for the simulations of air showers, it is very well known and its results are generally deemed trustworthy.

CORSIKA is a Monte Carlo program. Monte Carlo programs use probabilities and random number sequences to simulate the result for a system that has a wide range of possible outcomes for one set of initial conditions. This type of algorithm deserves the name of the gambling hot-spot, as probabilities play a large role in the simulations. Some of the probabilities involved in the case of astrophysics are cross-sections and decay-rates.

Today, CORSIKA is capable of simulating all kinds of events. Over a hundred types of primaries are available, and the program can be directed further by setting the magnetic field, angle of incidence, energy(range), interaction models and other aspects. A recent addition to the package enables the simulation of magnetic monopoles. Although they have not been observed, a good understanding of the electromagnetic interaction allows for credible monopole simulations.

5   Characterization of atmospheric monopoles

CORSIKA has been used for this research to simulate all air showers. For the simulations the EPOS-LHC[14] high-energy interaction model has been used, but both QGSJetII-04 and Sibyll 2.1 [15] [16] were also used to monitor the variations between interaction models. The differences in energy deposit, longitudinal development and secondary particles turned out to be negligible with respect to the other uncertainties. Therefore the EPOS-LHC model has been used for all further simulations.

It proved absolutely necessary to use the CONEX option for the simulations. CONEX greatly increases the speed of simulations for an alleged small loss in accuracy. Regrettably the increase in uncertainties could not be checked as monopole showers are required to be simulated using CONEX. Due to the limited availability of resources, not only monopole induced air showers but also all others were simulated using CONEX. This could be the source of larger inaccuracies than necessary or perhaps biased results.

Following the determination of the interaction model and necessary COR-SIKA settings, the invariance of air showers with respect to the monopole mass—as theory predicts—was checked. 300 monopoles of three masses: $10^5, 10^6$ and 10^7 GeV/c^2, were simulated and checked for a similar shower development and secondary particle counts. Studying a lower mass is unfortunately not a possibility as CORSIKA is coded to work with masses from 10^5 GeV/c^2 and higher, even though the mass settings set no lower bound. This is a flaw, and should be corrected in the future.

Another important prediction is the continuous, compact nature of monopole air showers. 1000 monopole showers were compared to 1000 proton and iron showers. These primaries are the ends of the cosmic ray spectrum, roughly representing the whole cosmic ray spectrum. The monopoles were initiated with discrete values for the energy every decade between 10^{10} and 10^{15} GeV. The nucleii were initiated with an energy of 10^6, 10^8 and 10^{10} GeV. When research lead to the more exotic, also photons of the same energies were simulated as well as muons with $E = 10^8$ and 10^{11} GeV. These particles were chosen specifically as hypothetically they could have very similar showers. Plots of the energy deposit per slant depth—the amount of atmosphere traversed, considering density—consequently reveal the differences in longitudinal shower characteristics. All energies were chosen such that showers with similar energy deposit are compared.

This is not necessarily precisely proportional to the amount of particles or energy present in the shower. However, since we are interested in similarity only within an order of magnitude, the energy deposit is a good enough criterion. On its own, the relations of energy present in the shower, energy deposit and number of particles can be interesting observables. But because none can be measured accurately by IceTop or IceCube and CORSIKA provides very uncertain data for the specific setup used, they are not investigated specifically. The energies mentioned here are used throughout the rest of this thesis, and no other.

The IceCube setup has a limited capability of distinguishing particle species. Therefore the shower content was studied for monopoles, cosmic rays, muons and photons. The ratio between the electromagnetic and the muonic shower parts have been considered in more detail, eventually leading to the lateral distribution of these ratios for all showers. They could be of significance, since—as you will remember—IceTop is specializing in determining these ratios specifically.

6 Results

All results presented here are extracted from the simulations described in the previous section. Not all results or plots are produced however, only those deemed relevant to the research question. After a check on the mass invariance of monopole showers, this section covers four aspects of air showers as potential distinguishing factors: longitudinal shower development, shower content, electromagnetic to muon ratio and shower size. The shower size is implicit; The energy range has been chosen for monopoles, and all other primary particles are given such an energy that they produce a shower of similar energy.
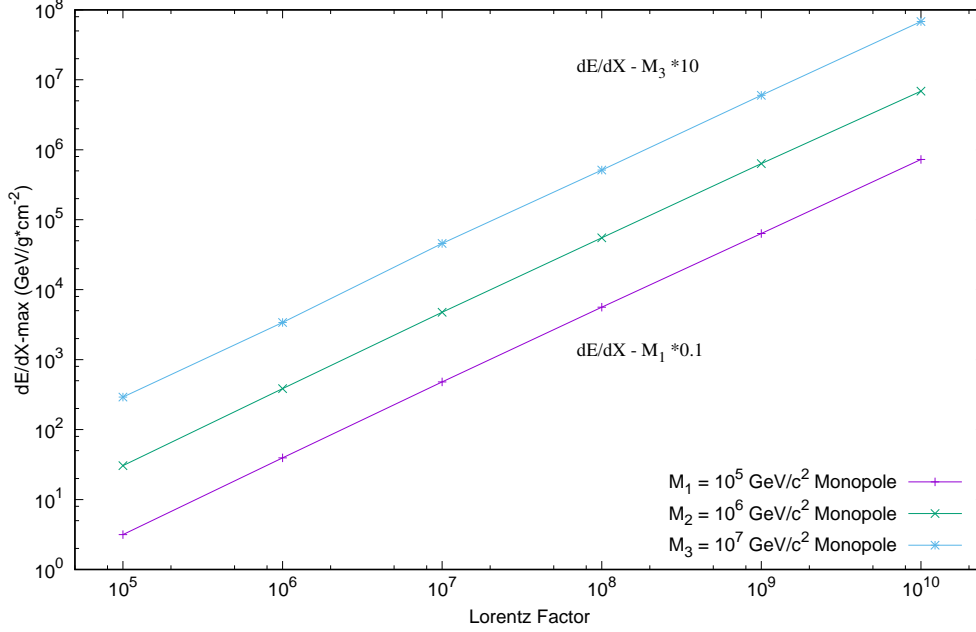
6.1 Mass invariance of monopole showers

Figure 5: Maximum energy deposit as a function of energy, for different masses.

Plotted for three different masses. M_1 and M_3 are shifted down and up, respectively, by a factor 10.

First of all the monopole simulations with different masses were analysed. The point where the shower reaches its maximum energy deposit is called the shower maximum. The energy deposit at shower maximum is plotted over the full energy range in figure 5. The vertical shift is the only separation of the different lines; normally they align almost perfectly. This confirms the prediction by Wick *et al.* that the energy deposit of a monopole shower is independent of the monopole mass. They also predict a slope of 1.28, or $dE/dX \propto \gamma^{1.28}$. This is also approximately found for all three masses.

In figure 5 we do not touch upon the longitudinal development of the showers, even though it was studied. The longitudinal results are not according to theoretical predictions. The cause of this is not thought to be physical of nature, and therefore ignored in this section. These results are treated separately in the appendix.

6.2 Longitudinal shower development and size

The longitudinal development of monopole showers and cosmic rays are plotted together in figure 6, and monopole showers together with showers from muons and photons in figure 7. The plots are deliberately separated for clarity. This reveals the fundamental difference between monopole and muon showers and all other types of showers, as well as the energies at which showers of different primaries have similar size.
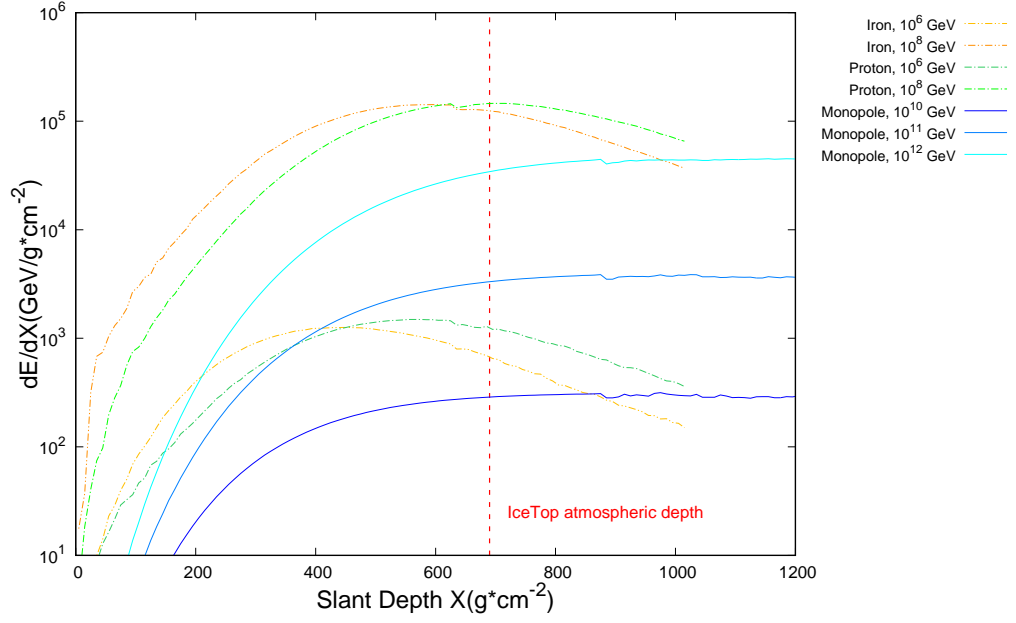
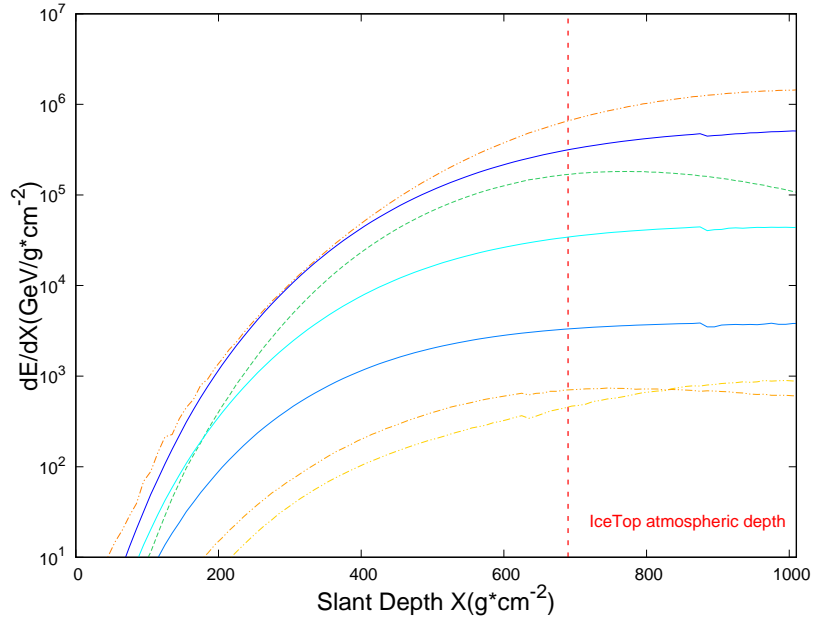Figure 6: Longitudinal shower development of several primaries and energies

Figure 7: Longitudinal shower development of several primaries and energies

As predicted, we clearly see that monopole showers start in the same fashion as any other air shower. It quickly increases in size but then reaches a maximum energy deposit later than other showers. A late maximum of the shower maximum is for example one of the characteristics of a monopole shower that the Pierre Auger collaboration uses as a cut in their CORSIKA motivated monopole search [8].

After the shower maximum the energy deposit of a monopole shower plateaus to a constant value, whereas for example a proton shower quickly diminishes. This is due to the continuous production of high energy particles as discussed in the theory, section 2. More surprising is the very similar behaviour of muon showers. They too produce a continuous shower. This result is important and easily measurable by a track-following detector. In this manner a photon shower could easily be distinguished from a monopole shower. For IceTop or any other surface detector this characteristic of muon and monopole showers is not detectable, however. Additionally, we see which energies correspond to same-size showers. Our choices for the energies of all primaries is based on these and similar plots.

Another straightforward result of these simulations are the sheer size (i.e. energy deposit per slant depth) of monopole air showers. The values taken for the monopole energy are reasonable theoretically speaking. The energies of the comparing air showers from other primaries are exotic, to say the least. Cosmic photons have never been observed anywhere near these energies, and cosmic rays or muons of these energies are hypothesized to have extremely low fluxes, especially since muons are very unstable. Therefore any observed extremely high energy event should be considered a potential magnetic monopole.

6.3   Shower content

The second aspect that is studied, is the shower content. The secondary particles that reach down to observation level are plotted over the energy range for all different primary particles except for muons in figure 8–11. This observation level is defined here as 1020 g/cm^2 even though IceTop is located at about 690 g/cm^2 because we assume an average geometry where the shower axis is tilted. Observation level corresponds to a shower reaching IceTop at an angle of about 45°.

We see that there is a modest difference between the iron and proton shower, as the proton shower contains fewer muons. This is not unexpected, as an iron nucleus scatters a lot more hadrons at the start of the shower. For monopoles, this difference is much larger compared to both proton and iron showers; Monopoles contain a hundred times more electrons and positrons. This is an important conclusion, because these are exactly the particles IceTop measures. It should be observed however that the cosmic rays gain a larger electromagnetic shower part at the high end of the energy spectrum. It could therefore be the case that at even higher energies than studied here, monopole showers can have a similar shower content to cosmic ray showers.

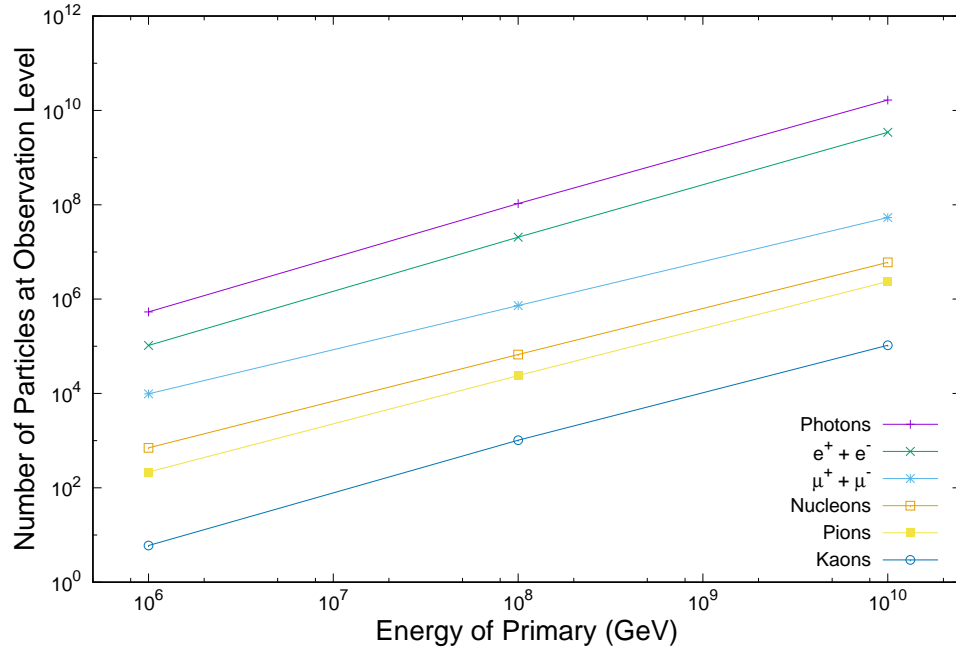The photon showers contain very similar relative amounts of particles as

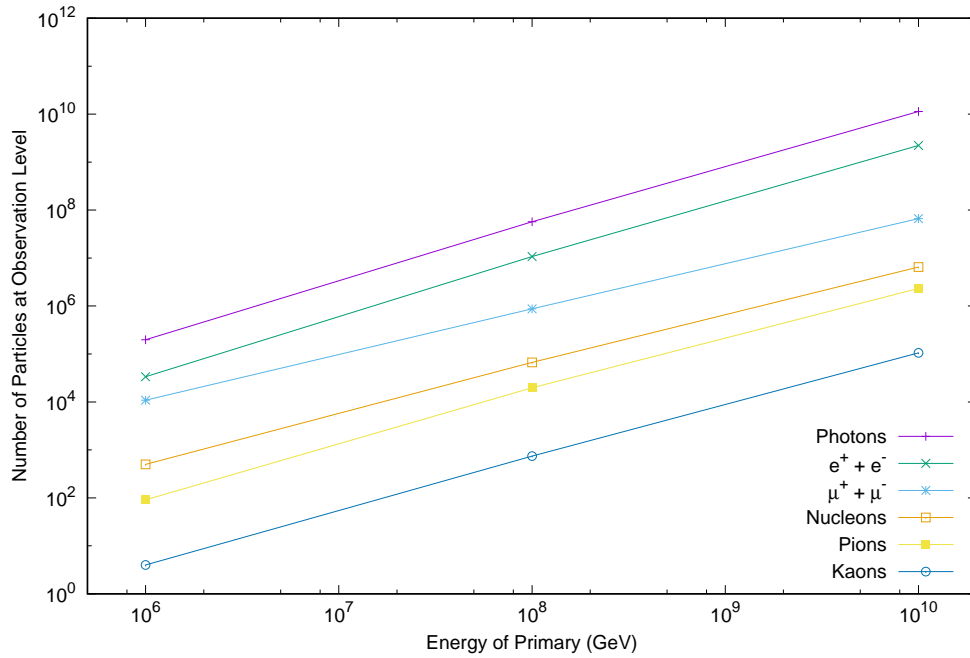Figure 8: Number of secondary particles, proton-induced shower

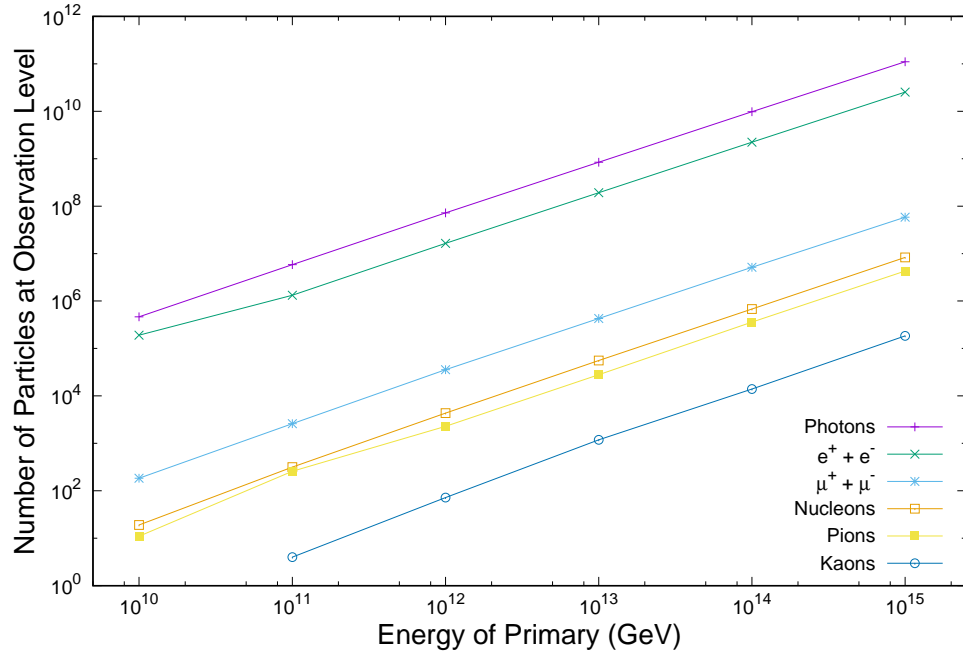Figure 9: Number of secondary particles, iron-induced shower

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Figure 10: Number of secondary particles, monopole-induced shower
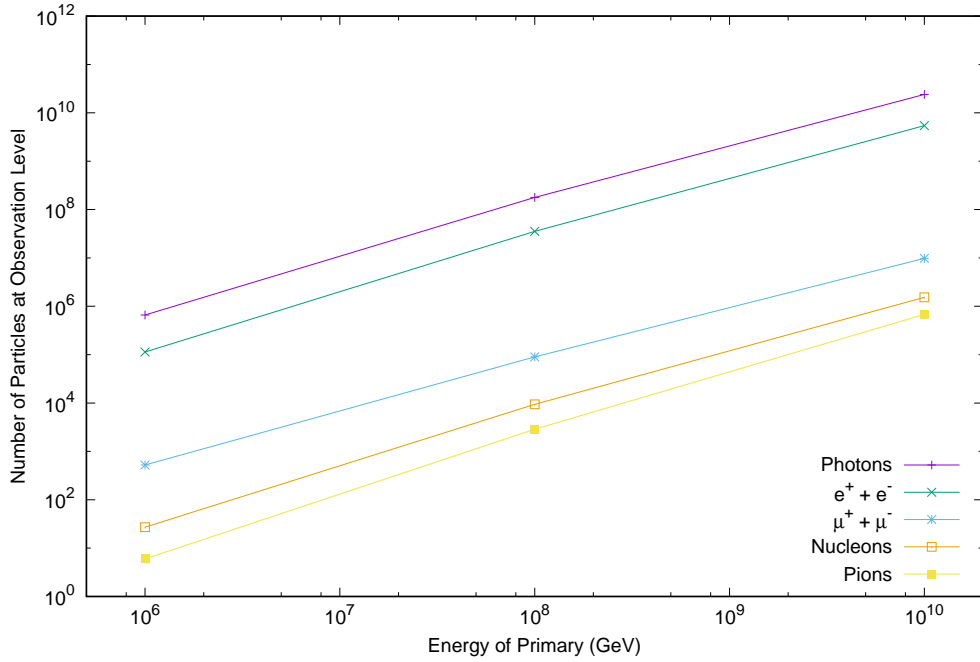

Figure 11: Number of secondary particles, photon-induced shower

monopole showers. A small difference can be observed for the amount of nucleons compared to the pions. Unfortunately the difference is perhaps too small to be significant and additionally cannot be observed by either a surface detector or even a track-following detector. There is not enough data available for muon shower plots, but the data suggests that the shower content is very similar to that of a monopole shower.

6.4   EM to muon ratio

We aim our attention at the ratio between the electromagnetic and the muonic part of the shower, as it has proven to be the most promising characteristic. In figure 12 this ratio for monopoles, cosmic rays and photons is plotted over the familiar energy range. The errors taken in the plot are conservative because no decisive answer could be given what kind of error CORSIKA provides in its output. Therefore the maximum and minimum values are taken to calculate the ratio while most likely the errors are smaller. Still, the difference between proton and iron showers is clearly visible, and in comparison to monopoles the gap is large.

For photons the previous findings are confirmed; their shower's EM to muon ratio is equal to that of a monopole shower, within the margin of error. It could be said that the monopole shower ratio has a negative slope, but this is based on only the first data point and deemed statistically insignificant. For cosmic rays and photonic showers, the ratio appears to be proportional to the energy of the primary. Although more data points should be studied as well as more simulations run for smaller errors, this signifies that these results are possibly not valid for the entire ultra-relativistic regime.

Additionally, photon showers produce a larger error. This is due to larger fluctuations between individual showers for longitudinal development as well as shower content and energy deposit at observation level. Photon showers are highly dependent on the first interaction(s). The type of this first interaction is determined probabilistically. This is in contrast with monopole showers that fluctuate less by their contunuous nature. Although this is an annoyance for distinction on an event to event basis, this characteristic could potentially be used if large amounts of very high energy photons are observed to falsify the hypothesis of a monopole signal. This is not a realistic scenario given the observed spectrum so far, however.

To investigate further, the lateral distribution of this ratio has been plotted in figure 13–17. The ratio is colour coded and plotted over 500 by 500 meter in the x-y plane. White bins signal that the numerator, the denominator or both have a value of zero. This reveals any asymetrics as well as the radial dependence. Again, there is a large difference between the cosmic rays and the monopoles. The ratio is different over the entire area of the shower, especially so at larger distances from the shower axis. Plots of the entire energy range have been made that show the same results.

Photon induced showers look almost identical to monopole showers over the full diameter. Muonic showers have very similar values for the ratios, but at
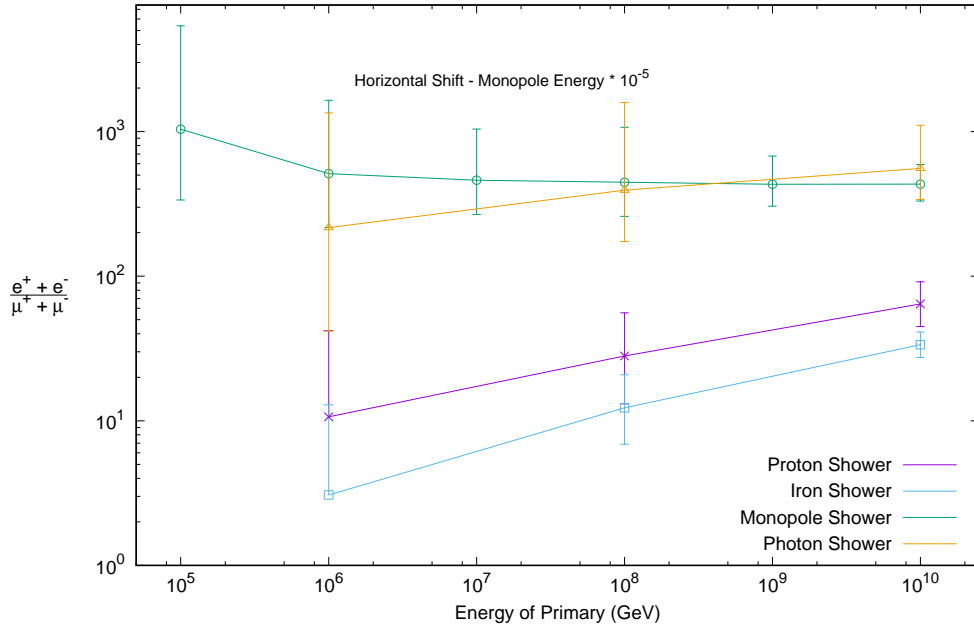
Figure 12: EM to muon ratio at observation level

larger distances more white bins appear. Somewhat less data has been obtained in the muon simulations, this accounts for some white bins. It also indicates that muon showers are (even) more compact than monopole showers. In order to compare shower diameters of monopoles and muons, more simulations should be run with identical energy deposits.

In order to characterize what makes a monopole shower unique and distinguishable from both the most common air showers as other more exotic showers, three aspects have been studied. The longitudinal development of the air shower, revealing the continuous nature of a monopole shower. Secondly the shower content, which showed that monopoles are mainly their electromagnetic part. Finally the ratio of the electromagnetic and muonic part has been studied, including laterally.

The longitudinal development of monopoles and muons proved fundamentally different than all other showers studied. Both monopoles and muons continuously produce showers along their track, resulting in a shower that remains the same size after its maximum rather than diminishing after a maximum is reached. For a track-following detector like IceCube this is a very strong quality to differentiate with. Additionally, these plots revealed that the energies of monopoles studied here produce air showers of a size incomparable to any observed showers so far. As such, any very high energy event should be considered a potential monopole event.

The particles present in the shower at observation level also revealed specific features. Monopole showers are chiefly electromagnetic in nature. Therefore many more electrons and positrons than muons can potentially be measured. IceTop is capable of measuring these particles specifically and as such, this result gives very good prospects for surface arrays like IceTop to detect a monopole-
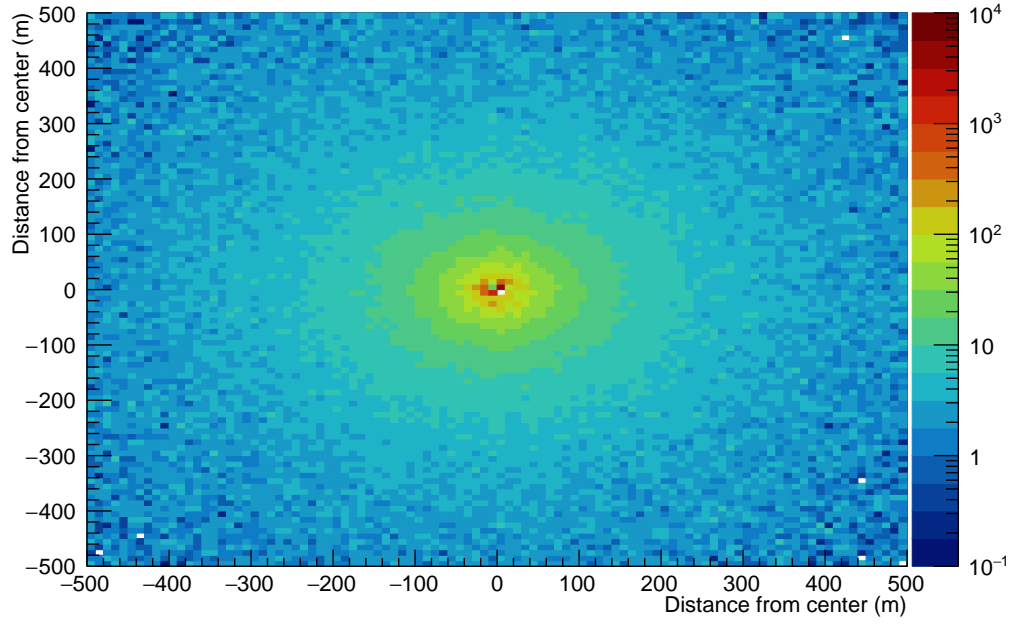
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Figure 13: lateral distribution of em to muon ratio, proton $- E = 10^8$ GeV
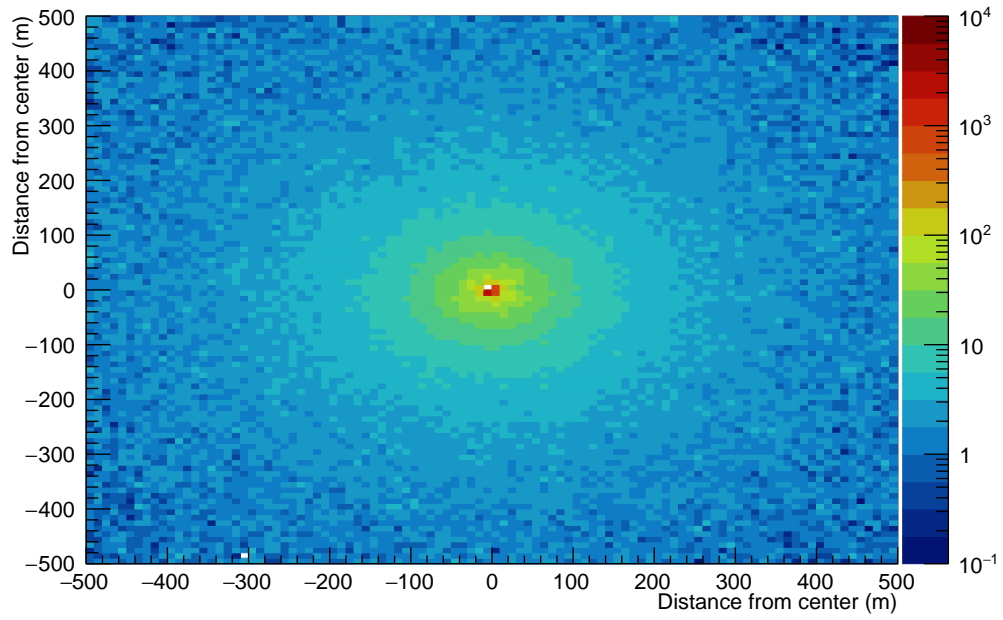

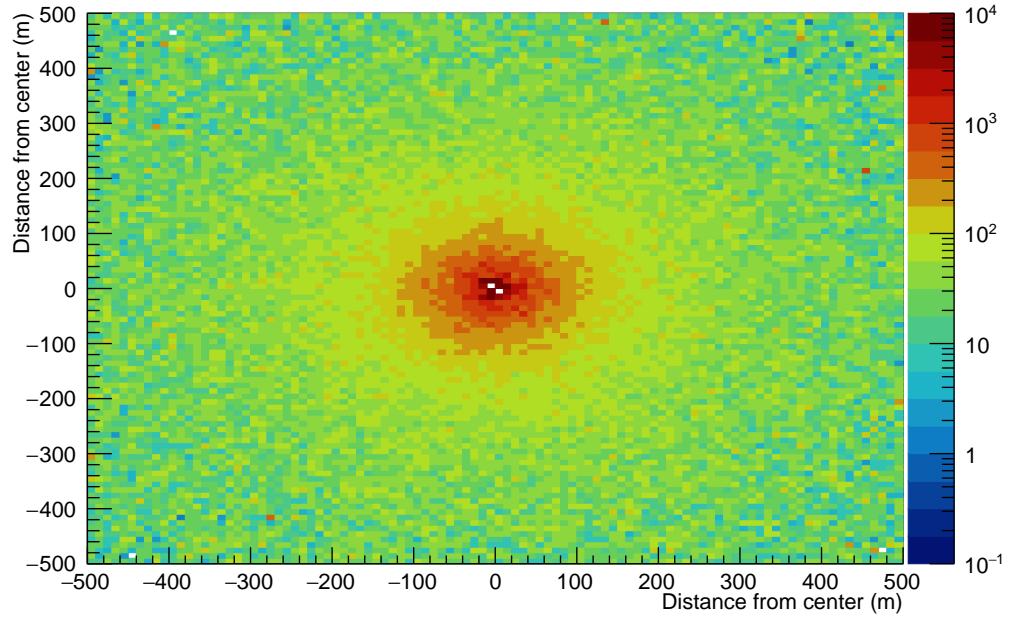Figure 14: lateral distribution of em to muon ratio, iron $- E = 10^8$ GeV

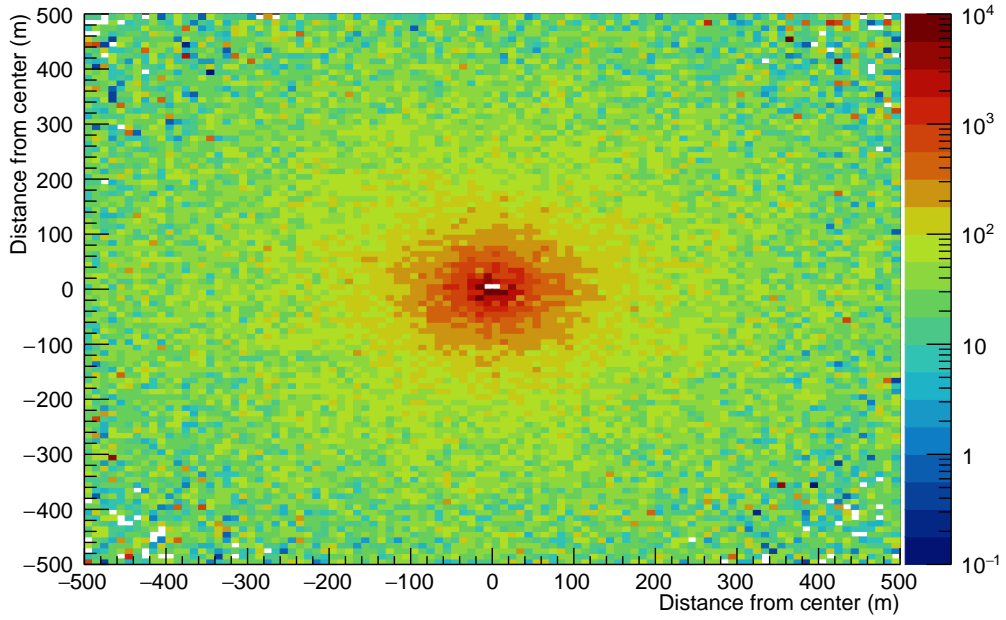Figure 15: lateral distribution of em to muon ratio, monopole – E = 10^{13} GeV

Figure 16: lateral distribution of em to muon ratio, photon – E = 10^{8} GeV
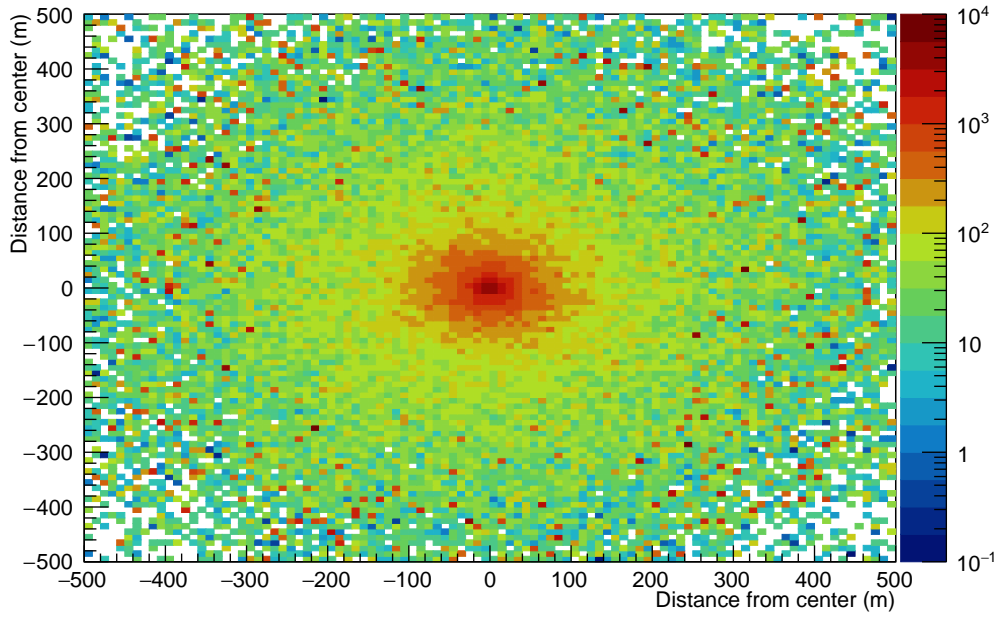
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Figure 17: lateral distribution of em to muon ratio, muon – $E = 10^{11}$ GeV

specific air shower signal. Very similar em to muon ratios were found for photons and muons.

Lastly, the ratio has been studied laterally, keeping in mind that IceTop (and other surface arrays) can determine primaries by means of this ratio at large distances from the shower centre. This showed that over the full diameter of the shower the ratio is different for monopoles. Both photons and muons produce similar results at observation level, making a distinction for surface arrays alone tough. The results did hint at more compact showers from muons, but no decisive answers can be given.

To summarize, cosmic rays are different from monopoles in both their longitudinal development and their shower content, specifically the electromagnetic to muon ratio. Photons share this longitudinal development with cosmic rays, but have a similar shower content as monopoles. Muons have both a continuous shower development and a shower content similar to that of monopoles.

7 Summary, conclusion and outlook

In this study monopole showers have been characterized. The primary focus has been the expected signal in surface arrays—IceTop specifically, and secondly the signal for any potential observatory. The characterization has been made based on simulations in CORSIKA. Simulations were run for intermediate mass monopoles of 10^5 GeV/c^2 with an energy between 10^{10} and 10^{15} GeV. These values have been chosen on the basis of previous theoretical knowledge. Simulations of cosmic rays, muons and photons were used as reference material.

Theoretical predictions of magnetic monopoles are abundant. More important predictions of theory are the possible masses and energies at which monopoles

can be found as well as the continuous nature of the expected air showers. Also the expected flux due to early universe symmetry breaking and the ability to produce air showers have been visited to found the basis for a monopole air shower search.

The characteristics of both IceTop and IceCube have been studied. This revealed that the best bet for IceTop to find monopole results is to look into the lateral distributions of the electromagnetic part and of the muonic part. Recent developments promise an accurate determination of primary type on an event to event basis, using IceTop data alone. IceCube measures high energy muons; virtually all other air shower particles are shielded by 1500 meters of ice. The amount and the energy distribution of these particles could be an interesting variable as well, but the number of simulations run were unfit for any accurate results.

The simulations displayed three important results. Firstly, the mass invariance of monopole air showers has been confirmed over a limited range of masses. Secondly, a continuous air shower was revealed by plots of the longitudinal shower development, plateauing after reaching the shower maximum. Finally, a study of the em to muon ratio of the shower content at observation level showed that monopoles contain many more electrons and positrons than conventional cosmic rays. Photon showers share this characteristic and so do muon showers, but they seem to be more compact than the other showers studied, although this cannot be said decisively.

Combining these results we can state with certainty that IceTop alone—and even more so combined with IceCube— is capable of distinguishing a high energy monopole event from any of the conventional signals. Including the longitudinal characteristics of the showers, photon showers are distinguishable as well. Only showers created by a very high energy muon look similar in all studied aspects. Identical results were found for muons and anti-muons. Muons are very unlikely to have travelled far because of their instability. As such, we expect such a muon to originate from a very high energy interaction close to earth.

The next steps to be taken in this line of research are the following. Firstly and most importantly more simulations should be run of the right energies to truly compare air showers. As these things are usually done on a cluster, in contrast to the use of a single computer here, this should easily be achievable. Another important factor could be the number of high energy muons and their distribution since IceCube will be able to measure them accurately. A requirement then is that CORSIKA should be able to simulate monopoles with different settings, specifically without thinning. Thinning reduces output files significantly, but is the main cause of uncertainties. Even though the uncertainties should be smaller and some aspects of the monopole shower in comparison to a muon-induced shower have to be studied more closely, the next step is of course to conduct an actual search with the found monopole shower characteristics. As data is already available from several large observatories, this is not a costly experiment and could improve upon the already established lower bounds of the monopole flux.
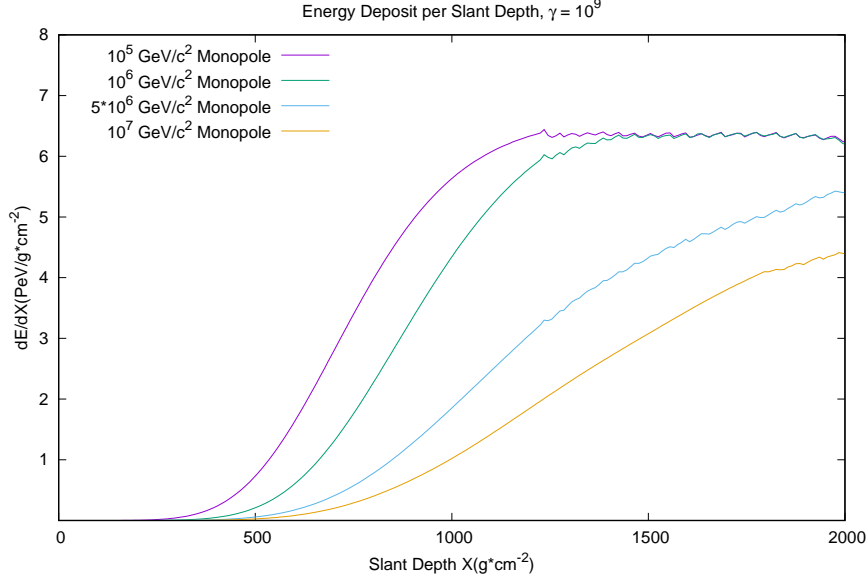
Appendix – mass dependency of shower maximum

Figure 18: Longitudinal development of monopole showers for several masses, $\gamma = 10^9$

The result presented here is done so because of its inconcistency with both theory and all other results. Because there is reason to believe that it is caused not because of unforeseen physics but because of some systematic error in CORSIKA.

In figure 18 the longitudinal development of monopole air showers—the energy deposit along the track—are plotted, similar to the plots in section 5.2. Now, air showers of monopoles of different masses but the same Lorentz factor are compared. Evidently, the showers take much longer to develop when initiated by a monopole with a higher mass. There are several reasons to assume that this apparent mass-dependency is not based in physics.

Firstly, the results show that a high-mass shower takes much longer to reach maximum energy deposit but does not deposit any more energy when that maximum is reached. This suggests that the same amount of energy is lost per unit time through the same interaction, naturally producing the same particles. This can only be explained if for a high-mass shower particles of much higher energy are produced, but a much smaller amount. The total energy deposit could then remain constant. This seems unlikely to begin with, and additionally no sign of this was found in the results.

Secondly, the theory treated in section 1 predicts nothing of the kind. According to Wick *et al.*, the dominant energy-loss mechanisms are oblivious to the monopole mass. All the interaction 'sees' is a localized magnetic charge with a certain speed.

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Finally, CORSIKA has on other occasions demonstrated that a monopole primary is not correctly integrated everywhere, as discussed in for example section 4. Adding that the option to simulate magnetic monopoles is recent and little used, it seems plausible that the cause should be sought for in simulations rather than physics. Although it has not been the goal of this study at all, an attempt could have been made to find the origin of these results. Unfortunately, CORSIKA is a hopeless case and prime example of 'scientific coding' i.e. little structure, huge pieces of code and poor documentation regarding the inner workings of the program. To some degree this was expected, and yet below expectation. As such, no attempt has been made to find the potential error.

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