Search for super-heavy Magnetic Monopoles with the IceCube Detector

by

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Abstract

The IceCube Neutrino Observatory is a kilometer-scale detector buried into the Antarctic ice. Its main task is to detect high energy cosmogenic neutrinos. However, due to its large detection volume, the IceCube detector will also be used to search for very different types of particles.
There are several hypothetic particles falling into the category 'super-heavy', e.g. magnetic monopoles predicted by GUT theories or supersymmetric particles like Q-balls. Under Rubakov-Callan effect, magnetic monopoles can catalyze proton decay when moving through matter. Depending on the catalysis cross section, the particles can leave a very distinct signature in the detector. Concentrating on monopoles with a high catalysis cross section, a cut strategy has been worked out to reduce the background while keeping as much of the simulated signal as possible. The results show that the strategy needs to be adapted to the monopole parameters.

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1 Introduction

By discovering the physical laws of electrodynamics in 1861, James Clerk Maxwell laid the foundation for the understanding of electric and magnetic fields and united them to become two aspects of the same phenomenon. In today's notation, the Maxwell equations read

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho & \qquad \nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} & \qquad \nabla \times \mathbf{B} &= \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{1}{c}\mathbf{j} \quad ,
\end{aligned}
\tag{1.1}
$$

using Heaviside-Lorentz units. However, despite the fact that these equations beautifully relate the electric to the magnetic force, one cannot fail to notice a fundamental asymmetry. While there exist source terms ρ and $\mathbf{j}$ for the electric field, the corresponding source terms for the magnetic field are absent. This is because so far, no one has ever observed a magnetic elementary charge, i.e. a magnetic monopole in nature.

Besides restoring the symmetry in Maxwell's equations (1.1), the existence of magnetic monopoles would be theoretically desirable for different reasons. Paul Dirac brought forward in 1931 an argument [1], stating that magnetic monopoles lead to the quantization condition

$$\frac{eg}{4\pi\hbar} = \frac{n}{2} \tag{1.2}$$

for the electric charge e, where g is the magnetic charge of the monopole. Reversing this argument, the known quantization of electric charge would imply the existence of magnetic monopoles [2]. Furthermore, the introduction of magnetic monopoles appears to be unavoidable when trying to formulate a Grand Unified Theory (GUT), which unifies the electroweak force with the strong force at very high energies [3]. Monopoles predicted by these theories are called GUT monopoles.

This report sums up a search for heavy GUT magnetic monopoles with the IceCube detector. Even though it is designed to detect high energy neutrinos of extragalactic origin, the large detection volume of the detector allows for the search of 'exotic particles' such as magnetic monopoles. In the remaining two sections of this chapter, the IceCube neutrino detector will be introduced (1.1) and a short explanation of the interaction of magnetic monopoles with matter will be given (1.2). The tools with which the data analysis is performed are introduced in Chapter 2, before presenting the analysis strategy and results in Chapter 3. A short conclusion with an outlook will complete the report.

1.1 The IceCube Experiment

Neutrinos are sometimes called ‘ideal messengers’ for astrophysical purposes, because their trajectory points directly back to their origin. This is because neutrinos only experience the weak force, which essentially means that they propagate all the way to the earth without interacting. Unfortunately, for the very same reason, the detection of neutrinos turns out to be very difficult. Only if a neutrino by chance interacts with an atom in matter, it is possible to detect it by measuring the secondary particle created in the interaction. Since these interactions are very rare, a large detector volume is needed.

The IceCube detector is located at the geographical South Pole and uses the Antarctic ice as target material for neutrinos. After completion in 2011, it will consist of 86 strings with 60 Digital Optical Modules (DOMs) each, giving a total number of 5160 DOMs. Each DOM is a self-contained detector able to measure Cherenkov radiation emitted by particles passing through the ice. In addition, 160 Cherenkov tanks on the surface form the IceTop detector, which measures cosmic rays. IceCube is designed to detect neutrinos with energies above some 100 GeV [5]. A sketch of IceCube can be seen in Fig. 1.1.

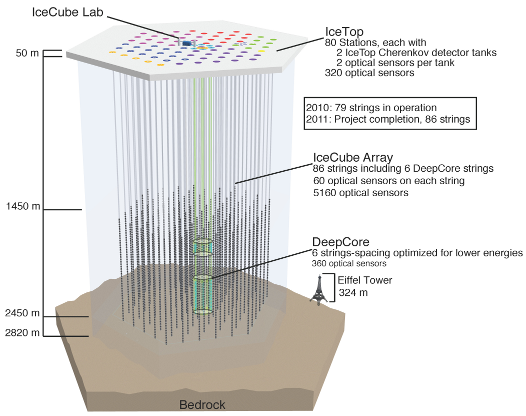

Figure 1.1: The IceCube detector [4].

To deploy the strings, holes of 2.5 km depth are melted into the ice, with a horizontal spacing of 125 m. Attached to the strings are the DOMs, at a depth of 1.45 km to 2.45 km, with a vertical distance of 17 m between them. The whole detection volume is 1 km^3. Inside the detector are IceCube’s predecessor AMANDA and the more densely instrumented Deep Core region, an extension of IceCube to detect neutrinos with lower energies.

The Digital Optical Modules consist of 35-cm-diameter pressure spheres, each containing a photomultiplier tube incl. electronics and a data aquisition system. The photomultiplier is sensitive to photons with wavelength 300-650 nm and has a gain of 10^7. Its peak quantum efficiency is 25 %. The data aquisition system is activated by a discriminator trigger, which fires at a voltage corresponding to 0.25 photoelectrons. The signal is digitized using an Analog Transient Waveform Digitizer (ATWD) and a fast Analog-to-Digital Converter (fADC) [5]. A trigger in one DOM is called a ‘launch’.

At the surface, launches are combined by a software trigger system, to decide wether an event occured or not. The two most important triggers are a multiplicity trigger, which requires 8 launches within a time of 5 µs, and a string trigger, which requires 5 launches in 7 adjacent DOMs on one string within 1 µs. When one of these conditions is fulfilled, all launches in the time window of $[-4, +6]$µs around the trigger time are combined to one event.

1.2 The Physics of Magnetic Monopoles

Magnetic monopoles that are predicted by GUT theories have masses of 10^7 - 10^{17} GeV. Because no processes in the current universe can create particles with these masses, they must have been produced in the very early universe, when higher energies were available [3]. This search concentrates on magnetic monopoles with large masses of 10^{14} - 10^{17}GeV, which are usually assumed to be subrelativistic.

Before explaining possible interactions of magnetic monopoles with matter, it should be mentioned that there exist other 'exotic particles', who share some properties with the monopoles. One example are so-called Q-balls, which are predicted by supersymmetric theories and possible candidates for dark matter. For lifetimes which exceed the age of the universe, masses of the order of 10^{16} TeV or more are required [6]. The interaction with matter is somewhat different for monopoles and Q-balls, however, the simulated signature in the detector is very similar. Thus, the term 'monopole' henceforth stands for magnetic monopole and Q-ball. This category furthermore contains so-called Nuclearites (or Strangelets), whose properties will not be explained here.

The Rubakov-Callan-effect

The Rubakov-Callan-effect is a mechanism that was suggested both by Rubakov and Callan around 1981 [7] [8]. It states that heavy GUT monopoles are able to catalyze nucleon decay, in particular proton decay. One of the main decay channels of the proton would be $e^+\pi^0$, where both the positron and the pion are much lighter than the proton and hence highly relativistic. The pion immediately decays into two photons and together with the positron, these will initiate an electromagnetic cascade via bremsstrahlung and pair production. Until their energy is too low, the charged particles in the cascade will emit Cherenkov radiation. The total energy of the cascade can be approximated to be the mass of the proton, about 1 GeV.

Two important free parameters which characterize the monopole are its velocity relative to the nucleon β and the catalysis cross section σ. According to Rubakov [7], the cross section is inversely proportional to the velocity,

$$\sigma = \sigma_0 \beta^{-1} \quad , \tag{1.3}$$

where σ_0 is an unknown parameter with a value typical of strong interactions ($10^{-25}\,\mathrm{cm}^2$ to 10^{-30} cm^2). Considering additional effects from angular momentum of the monopole-proton system, Arafune [9] found the relation for free protons to be

$$\sigma = 0.175 \frac{\sigma_0}{\beta^2} \quad . \tag{1.4}$$

The cross section can be expressed as a mean free path, using $\lambda = (n\sigma)^{-1}$, where n is the number density of protons. For ice, the final expression for the parameter σ_0 reads

$$\sigma_0 \approx \frac{\beta^2}{0.0175 \cdot N_A \cdot \lambda} \quad . \tag{1.5}$$

2 Data Analysis

2.1 Data Sets

In order to learn what a monopole signal in the data could look like, the detector response to magnetic monopoles has been simulated with two free parameters, the velocity β and the mean free path λ. The parameter values range from $\beta = 10^{-2}$ to $10^{-4.5}$ and $\lambda = 1$ mm to 1 m, as can be seen from the table in the left panel of Figure 2.1. The plot in the right panel shows the corresponding values of the cross section parameter σ_0. The green colored cells in the table mark combinations with high cross sections, which are the relevant ones in this search. Simulated monopoles with lower cross sections will be split up in many subsequent events in the detector, because the amount of light produced is not high enough to continuously fire the triggers.

$\beta \backslash \lambda$	1mm	1cm	10cm	1m
10^{-2}				
$10^{-2.5}$				
10^{-3}				
$10^{-3.5}$				
10^{-4}				
$10^{-4.5}$				

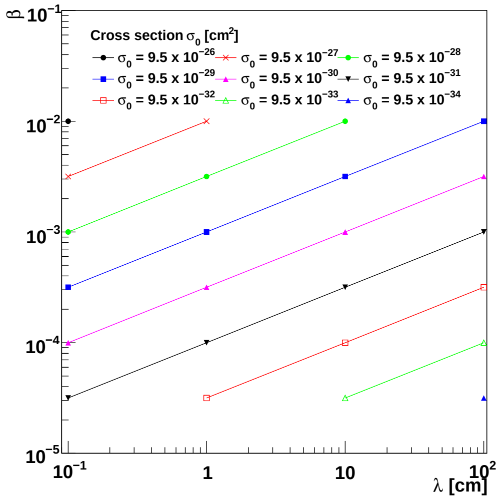

Figure 2.1: The parameter values for the signal simulation. *Left*: All but the red colored combinations have been simulated. This search concentrated on the green colored combinations. *Right*: The cross section parameter σ_0 as a function of β and λ.

In the course of the search, the simulated signal has to be compared with the expected background and, of course, the actual data. Here, the term 'background' refers to everything that is not a monopole, i.e. mainly atmospheric muons. This was simulated using the simulation software CORSIKA, including coincident muon showers. The data sample was a Burn Sample used for blind analysis, worth one month of data taking.

After being registered by the detector, every event has to pass through several filters before it can be analyzed. These filters apply cuts on a number of different variables.

This is done to reduce the number of obvious background events for a particular analysis, since the bandwidth of the data-transmitting satellite is limited. The filters are organized in so-called Levels, where data that has passed through all filters is dubbed 'Level 2'. To make a proper comparison between data and simulation, they have to be treated in the exact same way. Thus, the simulations were also processed to Level 2.

2.2 Observables used for the Analysis

Several observables have been used to compare the signal to the background and the data. They will be shortly introduced in the following, all of them are computed per event:

Event time - The event time is computed by subtracting the time of the first launch from the time of the final launch.

Track length - The track length is the distance between the two DOMs that were hit first and last respectively.

NChannel - Gives the number of different DOMs that were hit during the event. This is an estimate for the energy deposit in the detector.

NPE - The number of photoelectrons is the sum of all electrons registered by the photomultipliers. This is also a good estimate for the energy deposit and turned out to be more effective than NChannel in this analysis.

NStrings - The number of different strings that were hit in the event.

2.3 Event Display

To get an impression of what events in IceCube look like, two event displays are shown in Figure 2.2. The left panel shows the event from the data sample with the longest event time, 116µs. The origin of this event remains unknown, but a detector malfunction is likely the cause. The right panel shows a simulated monopole with $\lambda = 1\text{mm}$, $\beta = 10^{-2}$. Its event time was 426µs and it triggered launches in 450 DOMs (with a neighbour hit).

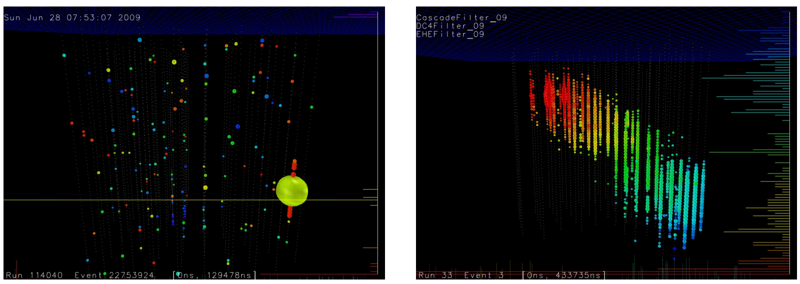

Figure 2.2: Examples of the event display. Launch time is color-coded from red to blue.

3 Results

To extract a possible signal from the data, one has to compare the simulated signal with the CORSIKA simulation of the background and with the data. In the case of a very weak signal, we expect the same behaviour for background and data. This will of course not always be achieved in practice, however, the agreement should be present to a reasonable degree. The cut strategy consists in finding variables where a clear distinction between the signal and background can be made. When applying the cut, a good compromise between cutting away as much background as possible and keeping as much signal as possible has to be found. This means achieving a high passing rate for signal events while the passing rate for background remains low. In analogy to the filter system, the cuts have been organized in levels. An overview over all cuts and the corresponding passing rates can be found in the appendix on page 12. All histograms shown in this chapter have been normalized to unity for comparison.

3.1 Cut on Event time (Level 3)

For a muon travelling at essentially the speed of light, it takes at most 6µs to cross the entire detection volume of IceCube. Adding 10µs for the trigger window, this gives a maximum event time of 16µs. This number becomes a little larger when considering that the IceTop detector has a trigger window of 20µs, but should always be below 30µs. The distribution of event times for a small sample of data and background can be seen in the upper left panel of Figure 3.1. There is a considerable amount of events with times greater than 30µs, which is most probably due to muons that coincidentally arrive at the same time and are registered as one event. The complete samples of data and background after the cut are shown in the upper right panel in Figure 3.1.

On the other hand, monopoles move through the detector at comparably low velocities. For example, a monopole with $\beta = 10^{-3}$ can stay inside the detector for several ms. The histograms in the two lower panels in Figure 3.1 show that most of the monopole events have times below 1 ms. This is because most of the monopoles are not registered as one event, but are split up into several subsequent ones with shorter event times. Nevertheless, a large fraction of signal events has event times considerably longer than the background events. Thus, a very effective method of reducing the background is to perform a cut at 30µs on all samples. The comparably low passing rates of this cut for the signal (14.5% to 84.5%) are acceptable when regarding the very low passing rates for the data and background (0.085% / 0.048%) respectively.

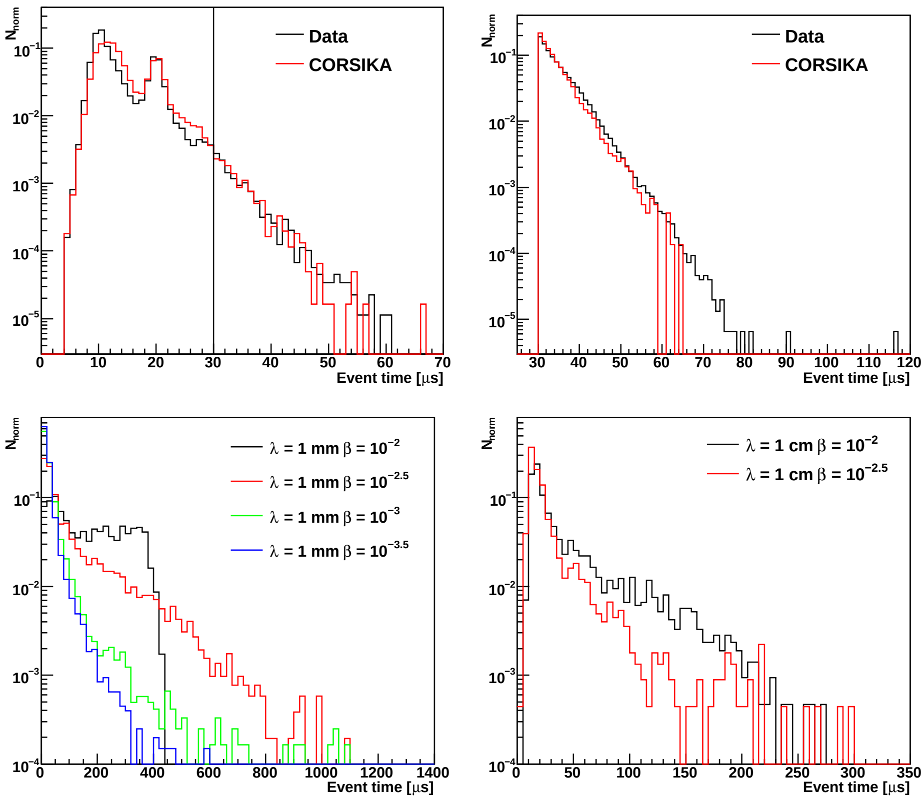

Figure 3.1: Histograms of the event times. *Upper Left*: Data and CORSIKA (subsample). *Upper Right*: Data and CORSIKA (after time cut at 30µs, complete sample). *Lower Left*: Signal, $\lambda = 1$ mm. *Lower Right*: Signal, $\lambda = 1$ cm.

3.2 Cut on NPE / Nstrings (Level 4)

Already from the time distributions in Figure 3.1, one can see that monopoles with different simulation parameters (i.e. λ and β) show a different behaviour. That makes it almost impossible to find variables to cut on which are suitable for all parameter values, other than the event time. Hence, two different cuts have been applied at this level, depending on the monopole parameters λ and β.

Cut on NPE (Level 4a)

For $\lambda = 1$ mm and $\beta = 10^{-2}, 10^{-2.5}$, a cut on the number of photoelectrons (NPE) at 100 is reasonable. These correspond to very high cross sections and lead to a large energy deposit in the detector, hence a large number of photoelectrons. A histogram with a line indicating the cut can be seen in the left panel of Figure 3.2. Here one can also see that the agreement between data and background is not very well in this variable. The second peak in the data histogram forms after the cut on the event time. However, what is more important, the agreement is fairly well in the region that is cut off.

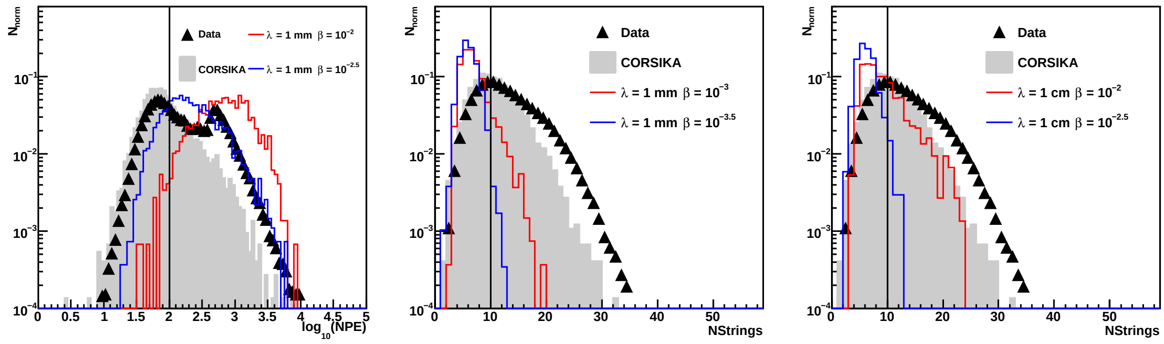

Figure 3.2: Histograms of the variables that were cut on at Level 4. The vertical lines mark the cut value. *Left*: Level 4a, NPE > 100. *Middle* and *Right*: Level 4b, NStrings < 10.

Cut on NStrings (Level 4b)

A different cut has been applied for the remaining region of the phase space. Here, the cross sections are lower and accordingly, the simulated monopole is likely to split up into several events with a small illuminated detector region each. Hence, the number of strings hit per event is smaller than for background events with muons crossing the whole detector. This can be seen in the histograms in the middle and right panel of Figure 3.2, which also show where the cut on NStrings has been applied.

3.3 Cut on NPE / NStrings / Track length (Level 5)

In order to find more cut variables, it is necessary to split up the signal simulations into more subsets. Starting from the two sets at Level 4, cuts are now applied on four different subsets, always including data and background (see table on page 12 for details).

Cut on NPE (Level 5a)

For the simulated monopoles with the highest cross section ($\lambda = 1\text{mm}$, $\beta = 10^{-2}$), NPE remains the only sensible variable to cut on. The number of photoelectrons is so high for these events because they illuminate a large part of the detector, see Figure 2.2(b) for an example. The distribution of NPE after the cut at Level 4 is shown in the upper left panel of Figure 3.3, together with a line indicating the new cut value. After this cut, the total passing ratios are: Data 0.03%, Background 0.007%, Signal 74.9%.

Cut on NStrings / Track length (Level 5b)

Two different cuts were applied to the simulated monopoles with $\lambda = 1\text{mm}$, $\beta = 10^{-2.5}$ at this level. Even though the corresponding cross section is fairly high, events already start to split up for these monopoles. Hence, the number of strings hit and the track length are smaller than for background muon events, which cross the whole detector. The upper middle and the upper right panel of Figure 3.3 show the histograms of these variables. The total passing ratios after the cuts: Data 0.005%, Background 0.002%, Signal 31.1%.

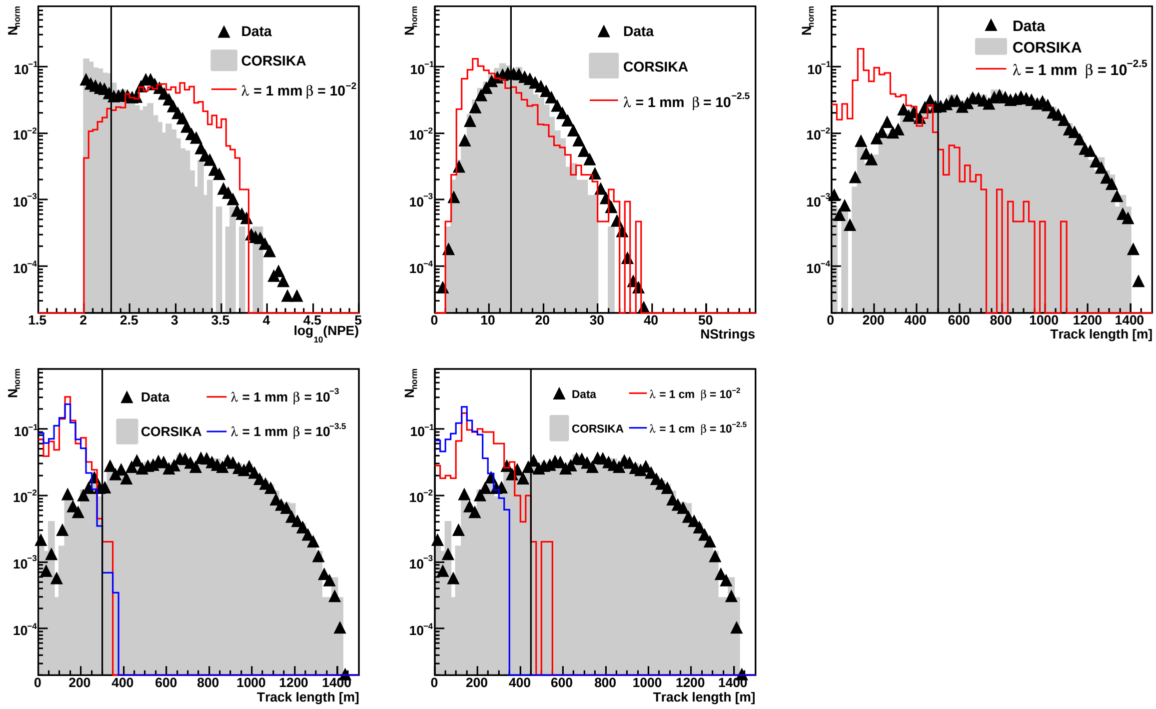

Figure 3.3: Histograms of the variables that were cut on at Level 5. The vertical lines mark the value at which was cut.
Upper Left: Level 5a, NPE > 200. *Upper Middle*: Level 5b, NStrings < 14.
Upper Right: Level 5b, Track length < 500m. *Lower Left*: Level 5c, Track length < 300m.
Lower Middle: Level 5d, Track length < 450m.

Cut on Track length (Level 5c and Level 5d)

The simulated monopoles with $\lambda = 1\text{mm}$, $\beta = 10^{-3}, 10^{-3.5}$ (Level 5c) and $\lambda = 1\text{cm}$, $\beta = 10^{-2}, 10^{-2.5}$ (Level 5d) all have cross sections low enough such that a significant number of them are registered as several subsequent events. This is why a cut on the track length is promising for these subsets. The histograms for Level 5c and Level 5d are shown in the two lower panels of Figure 3.3 respectively. Again, the vertical lines mark the cut which has been applied. The total passing ratios are:
Level 5c: Data 0.002%, Background 0.002%, Signal (20.3 / 14.3)%
Level 5d: Data 0.006%, Background 0.005%, Signal (23.3 / 14.6)%.

4 Conclusion

This work constitutes the first effort in finding a cut strategy for the search of superheavy, subrelativistic particles with the IceCube detector. Several theories predict particles with these properties, among them Grand Unified Theories (magnetic monopoles) and Supersymmetric Theories (Q-balls).

Using simulations of magnetic monopoles with high cross sections, a comparison between monopole signals and IceCube data as well as simulated background was made. The method to find a first cut strategy was to choose out of the most simple event variables those, which seem most promising to make a clear distinction between signal and background.

Results

The results show that the two free parameters of the monopole, its velocity β and its mean free path λ, have a great influence on the detected signal. Hence, different cut strategies have to be found for different parameters. In an first attempt to find a strategy that uses only simple event variables, the background could be suppressed by a factor of $10^{-4} - 10^{-5}$, while keeping some 10% of the signal. Remaining data events with long event times were found to be caused either by several coincident muons or by an obvious detector malfunction.

Outlook

Future work will not only include simulations of magnetic monopoles with low cross sections, but will also look for more complicated event variables to cut on. It appears to be very promising to use variables that describe the geometry of the event in the detector. While most monopoles leave cascade-like signatures, the main background consisting of coincident muons will look very different. For example, the mean distance of all optical modules that were hit from the 'center of gravity' (the center of the event), is a candidate for such a variable. A combination of new cut variables and the variables used in this analysis is expected to yield better passing ratios and substantially better background suppression.

5 Appendix

Level 3 Event time > 30µs					
Data: 0.00085 **CORSIKA**: 0.00048					
$\beta = 10^{-2}$, $\lambda = 1$ mm: 0.845	$\beta = 10^{-2.5}$, $\lambda = 1$ mm: 0.526	$\beta = 10^{-3}$, $\lambda = 1$ mm: 0.224	$\beta = 10^{-3.5}$, $\lambda = 1$ mm: 0.145	$\beta = 10^{-2}$, $\lambda = 1$ cm: 0.350	$\beta = 10^{-2.5}$, $\lambda = 1$ cm: 0.151
Level 4a NPE > 100		**Level 4b** NStrings < 10			
Data: 0.549 **CORSIKA**: 0.356		**Data**: 0.320 **CORSIKA**: 0.476			
$\beta = 10^{-2}$, $\lambda = 1$ mm: 0.965	$\beta = 10^{-2.5}$, $\lambda = 1$ mm: 0.782	$\beta = 10^{-3}$, $\lambda = 1$ mm: 0.913	$\beta = 10^{-3.5}$, $\lambda = 1$ mm: 0.992	$\beta = 10^{-2}$, $\lambda = 1$ cm: 0.670	$\beta = 10^{-2.5}$, $\lambda = 1$ cm: 0.968
Level 5a NPE > 200	**Level 5b** Nstrings <14 Track <500m	**Level 5c** Track < 300m		**Level 5d** Track < 450m	
D.: 0.692 **C.**: 0.412	**D.**: 0.114 **C.**: 0.134	**Data**: 0.085 **CORSIKA**: 0.082		**Data**: 0.215 **CORSIKA**: 0.202	
$\beta = 10^{-2}$, $\lambda = 1$ mm: 0.918	$\beta = 10^{-2.5}$, $\lambda = 1$ mm: 0.755	$\beta = 10^{-3}$, $\lambda = 1$ mm: 0.996	$\beta = 10^{-3.5}$, $\lambda = 1$ mm: 0.998	$\beta = 10^{-2}$, $\lambda = 1$ cm: 0.994	$\beta = 10^{-2.5}$, $\lambda = 1$ cm: 1.000
Level 3-5 Total passing rates:					
D.: $3 \cdot 10^{-4}$ **C.**: $7 \cdot 10^{-5}$	**D.**: $5 \cdot 10^{-5}$ **C.**: $2 \cdot 10^{-5}$	**Data**: $2 \cdot 10^{-5}$ **CORSIKA**: $2 \cdot 10^{-5}$		**Data**: $6 \cdot 10^{-5}$ **CORSIKA**: $5 \cdot 10^{-5}$	
$\beta = 10^{-2}$, $\lambda = 1$ mm: 0.749	$\beta = 10^{-2.5}$, $\lambda = 1$ mm: 0.311	$\beta = 10^{-3}$, $\lambda = 1$ mm: 0.203	$\beta = 10^{-3.5}$, $\lambda = 1$ mm: 0.143	$\beta = 10^{-2}$, $\lambda = 1$ cm: 0.233	$\beta = 10^{-2.5}$, $\lambda = 1$ cm: 0.146

Table 5.1: This schematic table shows the different cuts that have been applied to the data. The numbers give the passing ratio for the corresponding cut. Before the cuts, there were $1.77 \cdot 10^8$ data events and $1.52 \cdot 10^7$ CORSIKA background events.

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