MASTER

Cosmic rays: CORSIKA predictions for separated tracks

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Cosmic Rays: CORSIKA predictions for separated tracks

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Abstract

In the work presented, two separate topics were investigated, bound together in their respective dependence on cosmic ray simulations performed within the CORSIKA framework. The first part describes lateral separated muons and their large transverse momentum, i.e., $p_T > 2$ GeV/c. The analysis showed that the discrepancy between the laterally separated muon events detected with the IceCube detector and the predictions from simulation may be explained by the relative contribution of pion and kaon decays in cosmic ray showers. An increased contribution of prompt muons at higher $p_T$ was not found. The second part describes an estimation of the event rate of coincident up-going neutrino tracks from a single cosmic ray shower, in IceCube. The analysis showed that, with a estimated rate of $0.069 \pm 0.001$ events per year, coincident up-going neutrino tracks from a single cosmic ray shower may be a significant background for the on-going search for SUSY particles with IceCube.
То опа...
Contents

1 Introduction
  1.1 The History of Cosmic Rays ................................................. 1
  1.2 The Cosmic Ray Spectrum .................................................. 3
  1.3 Detection of Cosmic Rays ................................................... 3
  1.4 Measuring Cosmic Rays ...................................................... 7
  1.5 Simulating Cosmic Rays ..................................................... 10
  1.6 This Thesis ......................................................................... 11

2 The IceCube Detector
  2.1 Introduction ....................................................................... 13
  2.2 Particle Detection .............................................................. 14
  2.3 Events in IceCube ............................................................... 17

3 Cosmic Ray Simulation Framework
  3.1 Introduction ....................................................................... 21
  3.2 The geometry ..................................................................... 22
  3.3 Electromagnetic treatment ................................................... 25
  3.4 Decay treatment .................................................................. 26
  3.5 Hadronic interactions .......................................................... 29

4 Lateral Separated Muons
  4.1 Introduction ....................................................................... 31
  4.2 Model ............................................................................... 31
  4.3 Analysis ............................................................................. 33
  4.4 Results .............................................................................. 35
  4.5 Discussion ......................................................................... 37

5 High Transverse Momentum Prompt Muons
  5.1 Introduction ....................................................................... 41
  5.2 Model ............................................................................... 41
  5.3 Results .............................................................................. 44
  5.4 Discussion ......................................................................... 50
Introduction

1.1 The History of Cosmic Rays

Since 100 years, cosmic rays have been investigated by scientists all over the world. For a long time, scientist had believed that the background radiation they measured with electroscopes had a terrestrial origin. Several pioneers tried to test this hypothesis: In 1909 Theodor Wulf developed an electrometer and measured the radiation levels both at the top of the Eiffel Tower and on the ground. He found that radiation levels were higher at the top than at ground level, but his results were believed to be inconclusive [1]. In 1910 and 1911 Domenico Pacini observed changes in radiation levels over a lake and over the sea. He saw that radiation levels dropped at three meters below the surface, compared to measurements taken at the surface. He concluded that a certain part of radiation must be due to other sources than the Earth alone [2,3]. Unfortunately, his findings were published in Italian and only recently came to the attention of the public.

In 1912 Victor Hess performed several experiments: During untethered balloon flights, up to an altitude of 5300 meters, he demonstrated that the level of background radiation goes up with altitude. After his trips over a course of three years (1911-1913), Hess concluded that "a radiation of very high penetrating power enters our atmosphere from above." [4] These experiments would later, in 1936, win him the Nobel Prize for the discovery of cosmic rays [5,6].

After the discovery of cosmic rays, it took more than 30 years before the true nature of the cosmic radiation was established as positively charged nuclei reaching the top of the atmosphere [7]. Many hypotheses were proposed during the first few decades after the discovery, of which most notably the one of Robert Millikan [8]. Millikan suggested that cosmic rays were the result of electrons and protons combining to more complex nuclei, whilst releasing binding energy. In the 1920s, the only known elementary particles were electrons and ionized hydrogen, i.e., the proton. It was assumed that the formation of atomic nuclei took place throughout the universe while releasing binding energy in the form of gamma radiation, which would explain the cosmic radiation. Gamma radiation, though, is not influenced by the Earth’s magnetic...
1. INTRODUCTION

Figure 1.1: Victor Hess and his balloon in 2012, equipped with a radiation measurement apparatus.

A world wide survey conducted by Arthur Compton demonstrated conclusively that the intensity of cosmic radiation depended on the magnetic latitude [9]. Arthur Compton’s conclusion that cosmic radiation was predominantly charged particles resulted in a big debate between Compton and Millikan, which even made the front page of the New York Times on December 31, 1932: "MILLIKAN CLINGS TO PHOTON THEORY" [10].

In 1938 Pierre Auger and Roland Maze measured coinciding cosmic particles with a separation of 20 meters. This showed that the measured particles were only secondary particles from a common source [11]. Later Auger repeated the experiment in the Alps and showed that coinciding particles were observed with a separation up to 200 meters [12]. The observations made by Auger gave rise to the idea that the cosmic rays could only receive the large energy required for these relatively large separations in "electric fields of great extension". Auger and his colleagues discovered that there existed particles with an energy up to $10^{15}$ eV when the largest artificial energies and natural background radiation energies were only of the order of several MeV ($10^6$ eV).

After Auger’s experiments, in 1962 John Linsley observed a cosmic ray with an energy of $10^{20}$ eV [13]. This event was spread out over an area of 8 km$^2$. Using an array of scintillation detectors, Linsey was able to detect some of the estimated $5 \times 10^{10}$ secondary particles produced. Linsey’s array was one of the first large cosmic ray detectors to have measured the most energetic cosmic rays. The most energetic cosmic ray so far has been measured to be $3.2 \times 10^{20}$ eV (51 J). The detector that measured this ‘Oh-My-God’ particle was the Fly’s Eye detector in Utah, in 1991 [14]. To put this energy into perspective, consider the energy of a baseball traveling at a speed of 95 km per hour, packed into the core of an atom.
1.2 The Cosmic Ray Spectrum

After 100 years of research much progress has been made towards our understanding of the nature of cosmic rays. Especially the understanding of the cosmic ray spectrum has received much attention. Figure 1.2 shows the cosmic ray spectrum, i.e., the differential cosmic ray flux as a function of energy. The cosmic rays are composed of nuclei ranging from protons to iron, where protons are the most dominant contribution. As can be seen in Figure 1.2, the energies range from several MeV to hundreds of EeV ($10^6$ - $10^{20}$ eV). The differential cosmic ray flux is described by a power law:

$$\frac{dN}{dE} \sim E^{-\gamma},$$

(1.1)

with $N$ the number of particles, $E$ the particle energy and $\gamma$ the spectral index. $\gamma$ is taken to be roughly 3. This means that for every increase with a factor 10 in energy, the flux decreases with a factor of 1000. To put these numbers into perspective: Cosmic rays of 100 MeV have a flux of 1/cm$^2$/s, but cosmic rays with an energy of 100 EeV have a flux of only 1/km$^2$/century, as can be seen in Figure 1.2. The majority of the cosmic ray particles have a galactic origin and follow a spectrum with $\gamma = 2.7$. Around $5 \times 10^{15}$ eV the spectrum steepens gradually to $\gamma = 3.0$.

The absence of cosmic ray particles with an energy above $5 \times 10^{19}$ eV is commonly referred to as the Greisen-Zatsepin-Kuzmin (GZK) cutoff. Kenneth Greisen and Georgiy Zatsepin, together with Vadim Kuzmin, independently predicted in 1966 that cosmic particles can not reach energies above $5 \times 10^{19}$ eV. Their reasoning was that cosmic rays with an energy of and above the GZK cutoff will interact with Cosmic Microwave Background (CMB) photons. After interacting with the CMB photons, via a $\Delta$-resonance, pions are produced, carrying away a part of the energy and ultimately limiting the population in the highest energy regime [15, 16]. As a result of the GZK cutoff, the ’Oh-My-God’ particle was probably produced at a relatively nearby source.

1.3 Detection of Cosmic Rays

To get a better understanding of the nature of cosmic rays, several different detection methods have been developed. In the early days, the electrometer used by Victor Hess and later Geiger-Müller counters used by others could only provide a count rate. Later, using shielding techniques, an estimate of the energy could be made as well. These initial efforts were an import step towards a better understanding of the cosmic ray spectrum. What the experiments did not provide however, were answers about the composition and direction of the cosmic rays. Three important types of detectors are currently used in an attempt to address the aforementioned issues.
1. INTRODUCTION

Cosmic Ray Spectra of Various Experiments

Figure 1.2: The cosmic ray spectrum. Image courtesy of William F. Hanlon, University of Utah and [17]
1.3 Detection of Cosmic Rays

1.3.1 Scintillator Detectors

There are two types of scintillator detectors, i.e., liquid and solid. Two recent efforts each used one of the two types. The MACRO project used a liquid scintillator detector [18] and the KASCADE project used a solid scintillator detector [19]. Both types use a similar principle, only the scintillation materials differ. Figure [1.3] shows schematically what happens inside a scintillator detector. When a particle goes through the active medium, i.e., the scintillation material, electrons are freed or excited, which subsequently recombine or de-excite, emitting photons. The photons travel through the medium and are observed by photomultiplier tubes (PMTs). A good scintillation material is therefore a material that is dense, easily excited and transparent to the released photons. Inside a PMT the photon hits and photo-ionizes the cathode. A high electric potential consecutively accelerates the electrons to the next potential point, releasing even more electrons. In typically nine steps a large enough amount of electrons is accelerated to create an electric pulse that can be measured. Using a grid of scintillation sites, the angle, energy and spread of a cosmic ray shower can be estimated.

Figure 1.3: A schematic representation of a liquid scintillator detector

1.3.2 Atmospheric Fluorescence Detectors

Another successful design is the atmospheric fluorescence detector. One of the latest successful efforts is the HiRes project, the latest incarnation of the The Fly’s Eye project in Utah. One of the successes of The Fly’s Eye is confirming the GZK cutoff after promising results from the Auger collaboration. The HiRes detector showed a 5σ deficit in the region beyond the GZK-cutoff [20].

The atmospheric fluorescence technique is based on looking at the secondary light that is emitted by air molecules, excited by the incoming cosmic rays when they enter the atmosphere. This technique only works on dark moonless nights. To obtain the best possible conditions, the HiRes project is located in the desert in Utah, far away from light pollution caused by civilization. Figure [1.4] shows a schematic image of the HiRes detector. Note that for better
1. INTRODUCTION

spatial and temporal resolution two sites are used. The HiRes detector can with one site only observe a line in the sky and therefore only determine a plane of direction. Using two detector at sites far apart the intersection of the two planes gives a good measurement of the direction of the shower. The detector is able to observe air showers up to a distance of 40 km away, with an angular resolution of 1 sr [21].

Figure 1.4: A schematic representation of the HiRes detector. Each site can only determine the plane of the trajectory. Intersection of the two observed planes results in a measurement of the direction of the cosmic ray shower.

1.3.3 Cherenkov detectors

The currently most common type of cosmic ray detectors is based on Cherenkov radiation. The benefit of using Cherenkov light is that it provides the direction of the incoming particles in three dimensions, because it is emitted in a characteristic light cone. It can also benefit from large transparent and well shielded natural media, such as a glacier or a large body of water. The relatively large efforts going on at the moment of writing are: The Pierre Auger Observatory in Argentina [22], Antares and its successor KM3NeT in the Mediterranean sea [23] and IceCube on Antarctica [24].

Cherenkov light is emitted by the medium when charged particles transversing the medium are traveling faster than light travels in that medium. The effect is analogous to the shockwave that an airplane drags along when traveling faster than the speed of sound in air. Cherenkov light is emitted in a characteristic cone shape. The cone has an opening’s angle according to \( \cos(\theta) = 1/n\beta \), where \( n \) is the index of refraction and \( \beta \) the particle’s velocity divided by the speed of light. For ice this gives an angle of 41 degrees. The cone of light shines towards the particle’s direction of propagation, as shown in Figure 1.5. Chapter 2 will explain in more depth the workings of one of the Cherenkov detectors, i.e., the IceCube detector.
1.4 Measuring Cosmic Rays

As seen so far, the name cosmic ray is very misleading. We have known for almost 80 years that cosmic rays are actually charged particles, which have traveled over a great distance in space. From this point onward, the particle that enters the atmosphere will be mostly referred to as the primary particle and the products of a collision with a nucleus in the atmosphere will be referred to as secondaries.

When the primary particle enters the atmosphere, with a probability increasing with depth and energy, it will hit an atmospheric nucleus. When the primary particle hits the atmospheric nucleus, secondary particles are produced. The type of particles that are produced are predominantly pions and kaons with a trace of particles that contain heavier quarks. In the analyses presented here only particles containing one or more charm quarks are considered, which are mostly D-mesons.

Figure 1.6 shows a schematic drawing of the tree shape structure that is created after the initial collision of the primary particle. The first particles that are created have a relatively high chance of interacting with other atmospheric nuclei, whereas particles further down the tree will mainly create new particles through decay. Some of the decay channels result in muons, which are the particles the IceCube detector primarily detects. IceCube primarily detects muons because muons have a much longer mean free path than electrons and therefore emit Cherenkov light along a longer track. The typical mean free path of a muons in air is tens of kilometers where that of an electron is only several meters. In the ice both mean free paths are roughly 1000 times shorter, because the density is a 1000 times larger.

Figure 1.5: A schematic representation of a Cherenkov detector. The spheres are Digital Optical Modules housing a PMT and processing electronics. The blue cone is the Cherenkov light emitted by the medium.
Figure 1.6: A schematic representation of a cosmic ray shower. On the left a conventional CR shower is shown, where primarily Kaons and Pions are created on the first interaction. On the right a prompt CR shower is shown, where the first interaction creates a meson containing heavier quarks, i.e., charm and heavier. Prompt CRs are predicted to dominate above 100 TeV and conventional CRs below 100 TeV.
1.4 Measuring Cosmic Rays

Common decay channels that result in a muon are:

\[
\begin{align*}
\pi^\pm &\rightarrow \mu^\pm + \nu_\mu \\
K^\pm &\rightarrow \mu^\pm + \nu_\mu \\
K^0 &\rightarrow \pi^0 + \mu^\pm + \nu_\mu \\
K^+_L &\rightarrow \pi^0 + \mu^+ + \nu_\mu \\
D^+ &\rightarrow K^0 + \mu^+ + \nu_\mu \\
D^0 &\rightarrow K^- + \mu^+ + \nu_\mu \\
\end{align*}
\]

The decay channels to muons from D\(^+\) and D\(^0\) are only 7\% and 3.2\% respectively. The D-meson decay channels to kaons in these interactions yield almost no muons from kaon decay. The kaons that form in D-meson decays have a very large probability of interacting due to their high energy. Figure 1.7 shows the equal probability lines where interaction and decay are equally likely as a function of energy and atmospheric height, for the different mesons. Note that in typical muon interactions \(\mu(\text{+air}) \rightarrow \mu + e^+ + e^-\), muons keep their identity and only lose a fraction of their energy.

Figure 1.7: Lines show where the probability of decay and of interaction are equal, for different mesons. Image courtesy of Dr. Dieter Heck.

Figure 1.6 also shows the IceCube detector in relation to the atmosphere. As can be seen, in order to detect a muon, it will have to travel through approximately 1 km of ice. In addition to the ice, particles have to travel through several km of atmosphere in order to reach the top of the ice. Given that the lifetime of a muon and thus its mean free path scale with energy, one
1. INTRODUCTION

can imagine that the average energy of measured particles increases towards the horizon. The
ability of energy selection as a function of zenith angle, i.e., the angle between perpendicular
to the earth surface and the particle’s incoming trajectory is of particular use in this thesis.
When the angle of cosmic ray showers is large enough that practically no muons will make it to
the detector, the detector will still measure a small signal. At zenith angles of \( 80^\circ \) and higher
practically all particles but neutrinos are shielded by the Earth.

Neutrinos are detected in IceCube when the neutrinos undergo a Charged Current (CC)
interaction. A CC interaction is a destructive interaction after which a lepton is created,
matching the flavor of the neutrino, i.e., a muon neutrino creates a muon and an electron
neutrino an electron. Of the three neutrino flavors the muon neutrino is most easily detected,
because a muon has a relatively long mean free path compared to the mean free paths of the
electron and tau leptons. Although within the IceCube collaboration studies are performed
with regard to electron and tau neutrinos, this work will only discuss muon neutrinos. Any
further naming of neutrino flavors will be omitted from here on unless a comparison with other
flavors is made.

Figure 1.6 also shows the difference between a conventional and a prompt CR shower. Above
primary energies of \( 100 \) TeV, prompt showers are predicted to dominate. The different types of
showers have each a characteristic spectrum. Both atmospheric muon and neutrino fluxes, i.e.,
muons and neutrinos resulting from CRs follow a power law distribution as given in equation
\( \gamma = 3.7 \), but for prompt showers the spectral index goes to \( \gamma = 2.7 \). The change of the spectrum at high energies is the
most important aspect that resulted in the High \( p_T \) Muon analysis, described in chapter 4 and

1.5 Simulating Cosmic Rays

To get a better understanding of the mechanisms behind primary particles, interacting in the
atmosphere, models and a simulation framework were needed. The simulation framework used
to simulate cosmic ray showers was CORSIKA, initially developed by Dr. Dieter Heck in 1992
\[26\]. During the years that followed CORSIKA’s inception a variety of interaction models were
developed to test the latest insights in nuclear physic. Many of the advances made in the
interaction models are directly a result of work done by large particle accelerators, such as the
Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at Fermilab.

To simulate a cosmic ray shower, CORSIKA repeatedly walks through the following steps
until no particles remain to follow through the atmosphere:

1. Follow the primary particle through the atmosphere
2. Draw a height from a modeled probability distribution at which the particle interacts
3. Create a list of the secondary particles that were created
1.6 This Thesis

4 Take one particle of the list and follow it through the atmosphere or return to the previous
list if empty
5 Determine if the particle will reach sea level level. If so, write it out and return to step 4
6 Determine whether it will decay or interact
7 Return to step 3

The benefit of this approach is that it is very memory efficient, because only one extended
branch of the tree is kept in memory at any time during the calculation. Setting a minimum
energy threshold for each particle in the simulation aids to the simulation speed, because it
prunes the tree of particles. To determine the fate of every particle in a cosmic ray shower, two
different probability distributions are used for the path length of the particle, depending on
whether it will decay or interact. The shortest path length that is drawn from the distributions
determines the fate of the particle. The distributions are sampled using a random number
generator with a long repeat length, which is important because of the amount of showers that
needs to be simulated. Much simulation is often needed to create a data set that is comparable
in size and statistical significance to the actual data.

corsika has a proven track record of several decades. It has been updated and improved,
using new data from mainly accelerator experiments. Although corsika works well in for most
purposes, Lisa Gerhard discovered in her work for the IceCube collaboration that corsika
can not explain the transverse momentum spectrum observed with the IceCube detector. The
apparent discrepancy between simulation and data has been the inspiration for part of the work
described in this thesis. Details of the lateral separated muon and high transverse momentum
analysis will be discussed in chapter 4 and 5 respectively.

For the neutrino analysis that forms the other part of this thesis corsika was used as well.
In the energy region that the analysis was concerned with, the discrepancy investigated earlier
played no role and corsika was assumed to be correct.

1.6 This Thesis

The work presented here encompasses four parts divided over 7 chapters. Part one describes
the introductions to the topics important for the analyses presented. The introduction includes
an introduction to cosmic rays (this chapter), an overview of the IceCube detector in chapter
2 and a more in-depth overview of the simulation framework used in chapter 3. The second
part goes into the details of the actual analysis. The high $p_T$ muon analysis was a result of the
lateral separated muon analysis, primarily performed by Lisa Gerhard, which is described in
chapter 4. All other work was mainly performed by the author of this work.

The lateral separated muon analysis resulted in a significant discrepancy between the pre-
dictions from corsika simulations and the measured data. The hypothesis that the lateral
separation was a result of high $p_T$ muons, from decaying charm mesons was tested. Chapter 5
describes the analysis and results of this work. The third part of this work describes an analysis
of coincident up-going neutrinos in IceCube. Predictions made about a possible event rate of super symmetric tau leptons decaying near IceCube prompted an investigation of a possible background. Chapter 6 describes the analysis of cosmic ray neutrinos creating events in IceCube that would be indistinguishable of nearby super symmetric stau decay. Both analyses heavily depend on the simulation package CORSIKA, which was used to both make and explain predictions. Chapter 7 will describe the overall conclusion of the work presented and give an outlook and summary of remaining questions.
2

The IceCube Detector

2.1 Introduction

Since the discovery of neutrinos in 1956 [27] it took only two decades to realize that a Cherenkov detector with a large area was desirable to detect neutrinos with. In the past, calorimeters and water Cherenkov detectors dominated the field of neutrino observation. Although water Cherenkov detectors remained major contributors in the field of neutrino physics, e.g., the Antares experiment, further scaling became a large obstacle. Scaling is required to be able to detect particles with higher energies. One of the solutions proposed was a Cherenkov detector in ice. Using ice as a natural transparent medium scaling the size of the detector became significantly easier. This idea was put into practice in 1990s, when the construction of the AMANDA detector started at the South Pole, located in a glacier with a thickness of 2.8 km.

Using natural ice as a Cherenkov medium has several benefits. At a depth of more than 1400 meters the pressure is large enough for air bubbles to become ice-like crystals with a similar index of refraction, resulting in very clear ice. Aside from a clear medium, no support structure is needed, since the ice can function as a support structure, and there is very little background noise compared to water. In large water Cherenkov detectors placed in the ocean, backgrounds such as bioluminescence play a roll as well. The 2800 meter thick ice slap, located at the Amundsen-Scott South Pole Station was chosen as the location of the AMANDA detector and later for its successor IceCube. On investigation of the deeper ice it was found that the attenuation length of blue Cherenkov light, at a depth of more than 2000 meters, is more than 150 meters. The large attenuation length reflects the quality of the ice at the South Pole. Figure 2.1 shows the absorptivity, or inverse attenuation length, and the effective scattering coefficient as a function of depth and wavelength. In figure 2.1 lower values are better, because a lower absorptivity means that the light can travel further, which makes the entire detector more sensitive. A lower value for the effective scattering coefficient results in a higher path reconstruction accuracy, because more of the detected light has not scattered. Figure 2.1 also shows a clear peak around 2000 meters and is referred to as the dust layer. It is believed that the dust layer may have been caused by volcanic activity around 65,000 years ago [28].
2. THE ICECUBE DETECTOR

Soon after AMANDA’s completion in 2000, the detectors limitations became apparent and after an intermediary step to AMANDA II with updated electronics, a new design was proposed: IceCube (see Figure 2.2). The construction of the detector was completed in December 2010 and has a total volume of approximately 1 km$^3$. At the moment of writing, the IceCube collaboration consists of approximately 250 collaborators, spread across 38 institutions in 10 different countries. IceCube is called a neutrino telescope because it detects the Cherenkov light that is emitted by ice when charged particles pass through the detector. The charged particles are in turn a result of either cosmic rays or neutrinos undergoing either charged current or neutral current interactions.

2.2 Particle Detection

The IceCube detector is in effect a calorimeter that measures the energy loss of highly energetic charged particles in the ice. The volume of 1 km$^3$ primarily helps detecting high energy particles and less so aids the detector to differentiate between between electrons, muons and taus, which are the expected products of neutrinos of the corresponding flavors. Charged particles, e.g., a muons, are produced by either a charged current interaction inside or near the detector or a cosmic ray shower in the atmosphere. When a charged particle travels through the ice at a speed larger than the speed of light in ice, the medium radiates out light in a characteristic
2.2 Particle Detection

Figure 2.2: The IceCube detector with its predecessor AMANDA II shown as well.
cone shape following the particle through the ice. The emitted radiation is called Cherenkov radiation, named after Pavel Alekseyvich Cherenkov who first observed the effect in 1934 [29]. The effect holds a close analogy to the conic wave front created by an airplane traveling at super sonic speeds. Figure [2.3] shows a schematic drawing of the radiated wavefront.

\[ \theta = \arccos \frac{1}{\beta n}, \]  

(2.1)

The emission angle is given by equation (2.1). The solid blue line shows the distance light travels in a medium with refraction index \( n \) in time \( t \). The solid red line shows the distance the particle travels in the same time \( t \) with relative velocity \( \beta \). The gray dashed circles are the wave fronts originating from past moments, when the particle was at the position that lays in the centre of the circle.

The energy loss due to the emission of Cherenkov radiation is given by the Frank-Tamm formula [31]

\[ \frac{dE}{dx} = \frac{q^2}{4\pi} \int_{n(\omega) > 1/\beta} \mu(\omega)\omega \left(1 - \frac{1}{\beta^2 n(\omega)^2}\right) d\omega. \]  

(2.2)

Here \( \mu \) and \( n \) are the frequency dependent permeability and index of refraction, \( \omega \) the frequency of the radiation and \( q \) the charge of the particle. The integration can be done only for frequencies at which \( n(\omega) > 1/\beta \) and frequencies for which the medium is polarizable. In general, these are the photon frequencies for which the medium is transparent.

Different particles manifest themselves with different signatures in the ice. The track length of a muon is several kilometers, whereas an electron will give off its energy almost all at once. A tau can have a large track at high energies. To be able to discriminate between the different signatures, the IceCube detector has to be large enough. From the snow cover on top of the ice,
2.3 Events in IceCube

86 strings have been deployed inside the ice over a period of 7 years. Every partial deployment was immediately put to use, which gave rise to the names IC1, IC9, IC22, IC40, IC59, IC79 and IC86, referring to the number of strings, in different analyses. Each string consists of 60 Digital Optical Modules (DOMs) of which one is shown in Figure 2.4. A DOM is a glass pressurized sphere, containing a full light detection setup: A 10 inch Photo Multiplier Tube (PMT), high voltage production and a main board with readout and communication electronics [32]. Every DOM is hooked up to a communication cable to the surface, which are all connected to the counting house. In the counting house, the incoming light pulses are collected, filtered and stored in event files. An event is everything that takes place inside a time window of 20 $\mu$s around a trigger hit. A trigger hit occurs when at least 8 locally coincident, i.e., a set of next-to-nearest neighbor DOMs are detecting light within a 1 $\mu$s time window, hits take place.

Figure 2.4: A schematic drawing of a Digital Optical Module used in the IceCube detector. 60 DOMs are attached to one cable forming one measurement string. IceCube consists of 86 strings in total.

2.3 Events in IceCube

When an event takes place in IceCube the data is saved. The three different lepton flavors that can be detected each have a characteristic light pattern: Figure 2.5 (top) shows the characteristic track of light produced by a muon. In figure 2.5 (middle) the characteristic EM or hadronic shower of an electron is shown. The reason behind the short light burst is the very short mean free path of the electron. Figure 2.5 (bottom) shows the typical dumbbell or double-bang signature of a tau lepton. The double-bang is caused by the taus creation after a charged current interaction of a tau neutrino and subsequently its decay with a very dim track in between. In the detector visualizations, the size of the colored spheres represent the amount of
light detected with each DOM and the color represents the relative timing, red being early and blue being late.

In the analyses presented in this work, the detection of cosmic ray muon and up-going muon neutrinos are the only events considered. In the analysis of lateral separated muons from cosmic rays, due to high $p_T$, the muons are created directly in the cosmic rays and observed by IceCube. Figure 2.6 shows an example of a muon track that is significantly separated from the main bundle and would fit a two track hypothesis, whereas in figure 2.5 the muons are indiscernible. The clearly observable separation is a signature of a relatively large transverse momentum, $p_T$. Looking for two separable tracks gives us information about the transverse momentum and possibly about the composition of the cosmic ray spectrum.

The analysis that investigates coincident up-going neutrinos from cosmic rays the muons are a result of the two neutrinos undergoing a charged current interaction inside or near the detector. The reason that only muon neutrinos are considered in the latter analysis is that the direction of muon tracks can be determined with an accuracy of less than 1 degree, which is not possible for electron neutrinos and tau neutrinos are not created in conventional cosmic rays. Investigating double up-going cosmic ray muon neutrinos is of importance to the search for super symmetric taus. Super symmetric taus, or staus, are predicted to show up in the detector as two coincident up-going neutrinos.
Figure 2.5: IceCube event displays for (top) a muon or muon bundle IC40, a simulated $\nu_e$ (middle) and a simulated $\nu_\tau$ (bottom). Each point is from a single hit DOM and the size of the circles indicates amount of light detected. The color indicates the relative timing, from red (earliest) to blue (latest). From [33]
Figure 2.6: IceCube event display of a muon bundle (wide stroke of lit DOMs) and a laterally separated, high $p_T$, muon (dimly lit stroke of DOMs). The red solid lines are the results of a line fit for the tracks.
Cosmic Ray Simulation Framework

3.1 Introduction

In order to either analyze data on Extensive Air Showers (EAS), design experiments or test theoretical models, there is a need for detailed Monte Carlo simulations. To be able to compare simulation results with other groups and experiments, the widely accepted CORSIKA (Cosmic Ray simulations for KASCADE) framework is used in the IceCube collaboration. CORSIKA is a Monte Carlo program used to study the evolution of EAS in the atmosphere initiated by protons and heavier nuclei. CORSIKA was initially developed to support the KASCADE experiment with simulations [34] and since has been improved and further developed [26]. The CORSIKA simulation framework takes into account all the current knowledge of electromagnetic and high-energy interactions, mainly obtained with accelerators such as RHIC and the LHC. One of the key features of CORSIKA is the treatment of the correct statistical fluctuations around the mean of an observable. CORSIKA also treats the nucleon-air interactions, using several different interaction models, and explicitly follows secondary particles as well. The output of the simulations consists of all the secondary particles that reach observation height, which allows for a detailed analysis of the simulated showers. As an additional feature, the history of the particles that make it to the observation level can be kept by toggling the EHISTORY option in the CORSIKA simulation [35]. Unfortunately the latest version of CORSIKA does not write out this history. In order to retrieve the history information minor modifications were made to the source files. The changes made to the source only consisted of sending the internal storage of information about the parents and grand-parents of the observed particles to the output screen [35]. The changes give an extra handle to quantify differences between the different interaction models one can choose from.

CORSIKA consists of a few separate models, which each take care of their respective part of the simulation. The PYTHIA module treats all the decays [36], the GEISHA module takes care of the low energy and electromagnetic interactions [37], whereas the high energy interactions are
3. COSMIC RAY SIMULATION FRAMEWORK

handled by a variety of modules. The reason for a wide variety of modules for high energy interactions is that each of the modules explains and extrapolates the measurements of accelerator experiments differently. The main modules used in the IceCube collaboration are dpmjet [38], qgsjet [39] and sibyll [40]. The former two will be described in more detail in section 3.5.2 and 3.5.1 respectively. Because sibyll did not yield results that were significantly different from qgsjet in the laterally separated muons analysis, it will not be further investigated here.

3.2 The geometry

The basic routing inside corsika assumes a flat Earth. The assumption of a flat Earth is a good approximation up to 60° away from zenith, but further away from zenith and thus closer to the horizon, the air column transversed by particles grows more rapidly than one would expect from a curved Earth [41]. Figure 3.1 shows the depth of the atmosphere in kilometers as seen by particles starting at the edge of the atmosphere (112.8 km) as a function of angle away from zenith. As one can see, for larger angles the difference between a flat approximation and a curved Earth model becomes significant. Figure 3.2 shows the geometry and corresponding symbols of a flat Earth and a curved Earth geometry.

![Figure 3.1: The different slant depths in kilometers as a function of zenith angle, using a flat Earth model (red) and a curved Earth model (blue).](image)

What in a flat Earth is a straightforward zenith angle \( \theta \) is in a curved geometry less obvious and is called the apparent zenith angle \( \theta_{\text{app}} \). Equally the height \( h \) of a particle in a flat geometry, is called the apparent height \( h_{\text{app}} \) in the curved geometry. The following equations describe the relations between the the actual zenith angle \( \theta \) and apparent zenith angle \( \theta_{\text{app}} \), and the actual...
3.2 The geometry

Figure 3.2: A schematic drawing of the parameters involved in particle tracking inside the atmosphere. In both geometries $h$ is the height above the surface, $\theta$ the angle with local zenith, $L$ the track length of the particle and $r$ the distance along the surface of the Earth. In the curved geometry (right) the parameters are different in the frame of reference of the detector, opposed to the flat approximation (left). In the curved geometry $\theta_{\text{app}}$ is the apparent zenith angle and $h_{\text{app}}$ the apparent height as seen from the detector. To calculate the apparent value, in addition to the other parameters, the radius of the Earth $R_E$ is used and the openings angle with zenith measured at the Earth’s core $\theta_E$ is calculated. For both geometries $h_{\text{obs}}$ is the height of the observation plane measured from sea level and $h_{\text{atm}}$ the height of the atmosphere, here 112.8 km.
3. COSMIC RAY SIMULATION FRAMEWORK

height $h$ and apparent height $h_{app}$:

$$\theta_E = \frac{r}{R_E}$$  \hspace{1cm} (3.1)

$$\theta_{app} = \theta_E + \theta$$  \hspace{1cm} (3.2)

$$R_o = R_E + h_{obs}$$  \hspace{1cm} (3.3)

$$R_h = R_E + h$$  \hspace{1cm} (3.4)

$$L^2 = R_o^2 + R_h^2 - 2R_oR_h\cos(\theta_E)$$  \hspace{1cm} (3.5)

$$h_{app} = L\cos(\theta_{app}) + h_{obs},$$  \hspace{1cm} (3.6)

where $R_E$ is the average radius of the Earth, $r$ the radial distance of the given position of the particle’s position projected perpendicular to the surface of the Earth, $h_{obs}$ the height of the observation plain and $L$ the length of line connecting the particle’s point of entering the atmosphere and the origin of the detector frame.

To give an accurate description of the atmosphere in a curved Earth model, a full integration would be required along the particles trajectory. To alleviate this computational burden an approximation was made inside CORSIKA. For a certain maximum displacement along the surface of the Earth the atmosphere is assumed to be planar. For showers that start at an angle of less that 60° this is results in almost the same treatment as a flat Earth model. For larger angles the maximum displacement is gradually set to 6 km at sea level up to 20 km at the top the atmosphere. The approximation results in a relative error of less than 0.5% in the used thickness, i.e., the water equivalent distance, of the atmosphere [41].

As shown in figure 3.1, the depth of the atmosphere increases towards larger zenith angles. A non-negligible effect of this increase in depth is the broadening of the probability density function that describes the probability of a primary particle interacting with a nucleus as a function of depth. The broadening effect results in a higher average height at which primary particles interact towards higher zenith angles.

The atmosphere is used across all modules and is an important part of the simulations. In CORSIKA the atmosphere is described using five layers, each a best fit to pressure measurements taken by weather organizations. Layers are described using the following equations, describing the height $h$ dependent mass overburden $T(h)$:

$$T(h) = a_i + b_ie^{-h/c_i} \quad i = 1, \ldots, 4$$  \hspace{1cm} (3.7)

$$T(h) = a_5 - b_5 \frac{h}{c_5}$$  \hspace{1cm} (3.8)

where $a_i$, $b_i$ and $c_i$ are measured constants and selected such that the layers form a differentiable continues profile. Note that in the fifth layer the mass overburden decreases linearly and vanished at $h = 112.8$ km. The term mass overburden is used to describe the length of a path normalized to the density of water, expressed in units of g/cm$^2$. 


3.3 Electromagnetic treatment

The nature of muons, unlike electrons, allows them to travel over large distances. Therefore, CORSIKA takes several electromagnetic treatments into account. The larges influences on a muon’s trajectory are multiple scattering, ionization energy loss and magnetic field bending.

To incorporate the energy loss due to ionization the Bethe-Bloch stopping power formula is used:

\[
dE_i = \frac{\lambda q^2}{\beta^2} \kappa_1 \left( \ln(\gamma^2 - 1) - \beta^2 + \kappa_2 \right),
\]

where \(\lambda\) is the thickness of the medium, \(\beta\) the velocity of the particle in the laboratory frame as a fraction of the speed of light, \(\gamma\) the particle’s Lorentz factor and \(q\) is the charge of the particle in units of \(e\). The constants \(\kappa_1 = 0.153287\) MeV g\(^{-1}\) cm\(^2\) and \(\kappa_2 = 9.386417\) are taken from the table for dry air [42]. Muons with an energy in excess of 2 TeV suffer from additional energy losses due to bremsstrahlung and pair production (\(e^+ e^-\)). The energy loss of muons as a function of energy is shown in figure 3.3.

![Figure 3.3: The energy loss of muons in air as a function of its Lorentz factor. Note the separate contributions of ionization (dashed line) and direct pair production (dotted line). Image with courtesy of dr. Dieter Heck [26]](image)

When particles are scattered in the atmosphere they are predominantly scattered due to the Coulomb field of nuclei in the air. Because the nuclei in the air are much heavier than the all long-lived secondary particles (Nitrogen \(\approx 13\) GeV/c\(^2\) vs. muon \(\approx 106\) MeV/c\(^2\)), the direction of the particles is altered but not the particle’s energy. In CORSIKA the process of Coulomb multiple scattering is only considered for muons and only once halfway each tracking step. The angular distribution of the multiple scattering is described by Molière’s theory [43].
The scattering treatment of high energy and/or heavy particles is considered negligible and thus not treated.

The deflection in Earth’s magnetic field is a result of the Lorentz force acting on a charged particle moving in a magnetic field. The total angular deflection $\alpha$ is approximated by:

$$\alpha \approx \ell \frac{q \vec{p} \times \vec{B}}{p^2},$$

in which $q$ is the particle’s charge, $\vec{p}$ the momentum traveling along the particle’s path with length $\ell$ and $\vec{B}$ the approximately uniform magnetic field. The approximation only hold for small angle corrections. Another way of looking at the influence of the magnetic field is by looking at the gyroradius $r_g$, which is calculated as follows:

$$r_g = 3.3 \times \frac{p}{Z|B|},$$

with $p$ the momentum of the particle perpendicular to the magnetic field in GeV/c, $B$ the magnetic field strength in Tesla and $Z$ the charge of the particle in units of $e$. The calculation is only valid for particles traveling perpendicular to the magnetic field. The gyroradius actually increases with a decreasing perpendicular component, due to relativistic effects. The magnetic field is characterized by the magnetic field strength $B_E$, its declination angle $\delta$ and its inclination angle $\vartheta$. At the location of the IceCube detector the values are [44]:

$$B_E = 55.1 \, \mu T, \quad \delta = -27\,^\circ\,3\,' \quad \text{and} \quad \vartheta = -72\,^\circ\,25\,',$$

which corresponds to the components

$$B_x = 16.4 \, \mu T \quad \text{and} \quad B_z = -53.4 \, \mu T,$$

while $B_y = 0$ because the coordinate system is pointed with the x-axis towards the magnetic pole.

### 3.4 Decay treatment

Most of the particles created in a cosmic ray shower are unstable and are likely to decay before interacting. $\pi^0$ and $\eta$ mesons, as well as resonance states, have such a short life time that the change of interacting before decaying is negligible. The range of muons is only limited by its lifetime and neutrons are considered stable inside CORSIKA. For all other particles there is a competition between interacting and decay. The decision towards what the fait of a particle will be is solely dependent on its free path. Note that CORSIKA only treats branching ratios that are more likely than 1%.

#### 3.4.1 Free path

To determine the fait of a unstable particle two random variables have to be determined: The interaction length and the decay length, where both are drawn independently from each other.
The shortest length drawn will be the actual path length of the particle and will also decide whether a particle will interact or decay [26]. Muons, for example, have the following mean free paths and corresponding probability density functions for interactions:

\[ \lambda_{\text{int}} = \frac{m_{\text{air}}}{\sigma_{\text{int}}} \]  

(3.14)

where \( \lambda_{\text{int}} \) is the mean free path in g/cm\(^2\) and \( \sigma_{\text{int}} \) is the interaction cross section due to bremsstrahlung and pair production. The molar mass of air is \( m_{\text{air}} = 14.54 \text{ g/mol} \). The corresponding probability of a muons transversing a thinkness \( \lambda \) without interacting is then

\[ P_{\text{int}}(\lambda) = \frac{1}{\lambda_{\text{int}}} e^{-\lambda/\lambda_{\text{int}}} \]  

(3.15)

For decays the mean path length \( \ell \) is determined by

\[ \ell_D = c \tau_\mu \gamma_\mu \beta_\mu \]  

(3.16)

with \( c \) the speed of light, \( \tau_\mu \) the muon life time at rest, \( \gamma_\mu \) the Lorentz factor and \( \beta_\mu \) the velocity of the muon in units of \( c \). The corresponding probability of a muon traveling a certain length \( \ell \), in cm, is

\[ P_D(\ell) = \frac{1}{\ell_D} e^{-\ell/\ell_D}. \]  

(3.17)

To convert the probability distribution into one that depends on the path length in g/cm\(^2\) the following conversions are required:

\[ f = \lambda(\ell, h_0, \theta) = \frac{T(h) - T(h_0)}{\cos(\theta)} \]  

(3.18)

\[ P_D(\lambda) = P_D(\ell) \frac{d\ell}{d\lambda} = P_D(f^{-1}(\lambda)) \frac{d(f^{-1}(\lambda))}{d\lambda} \]  

(3.19)

where \( f^{-1} \) represents the inverse function of \( f \) and \( T \) the mass overburden mentioned in equations (3.7) and (3.8). Note that these examples are only valid under the assumption that the kinetic energy of the muons does not change during transport.

### 3.4.2 Muons

Muons can only decay to an electron and two neutrinos \( \mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu \). The decay of a muon only has to be considered when its free path, or track length, is not long enough to reach the observation height. The energy distribution of the electron in the cm system is

\[ \frac{dN_e}{dE_{e,\text{cm}}} \propto 3 \frac{m^2_\mu + m^2_e}{2m_\mu} E^2_{e,\text{cm}} - 2E^3_{e,\text{cm}} \]  

(3.20)

for which the Electron energy \( E_{e,\text{cm}} \) is taken at random.
3. COSMIC RAY SIMULATION FRAMEWORK

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Ratio (%)</th>
<th>Decay mode</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{\pm} \rightarrow \mu^{\pm} + \nu$</td>
<td>63.5</td>
<td>$K_{S}^{0} \rightarrow \pi^{0} + \pi^{0}$</td>
<td>68.6</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^{\pm} + \pi^{0}$</td>
<td>21.2</td>
<td>$K_{S}^{0} \rightarrow \pi^{\pm} + \pi^{0}$</td>
<td>31.4</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^{\pm} + \pi^{\pm} + \pi^{\mp}$</td>
<td>5.6</td>
<td>$K_{S}^{0} \rightarrow \pi^{\pm} + e^{\mp} + \nu$</td>
<td>38.7</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^{0} + e^{\pm} + \nu$</td>
<td>4.8</td>
<td>$K_{S}^{0} \rightarrow \pi^{\pm} + \mu^{\mp} + \nu$</td>
<td>27.1</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^{0} + \mu^{\pm} + \nu$</td>
<td>3.2</td>
<td>$K_{S}^{0} \rightarrow \pi^{0} + \pi^{0} + \pi^{0}$</td>
<td>21.8</td>
</tr>
<tr>
<td>$K^{\pm} \rightarrow \pi^{0} + \pi^{0} + \pi^{0}$</td>
<td>1.7</td>
<td>$K_{S}^{0} \rightarrow \pi^{+} + \pi^{-} + \pi^{0}$</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Table 3.1: Most common Kaon decay modes and their respective branching ratios [26]

3.4.3 Pions

Neutral pions ($\pi^{0}$) decay 98.8% of the time into two photons $\pi^{0} \rightarrow \gamma + \gamma$, which are emitted in opposite directions with a center of mass energy equal to half the pions mass. Together with the Dalitz decay $\pi^{0} \rightarrow e^{+} + e^{-} + \gamma$, which happens 1.2% of the time, this decay is not of importance to this analysis. It is however a part of the CORSIKA framework.

The decay of charged pions $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ is one of the largest sources of muons within a cosmic ray shower. The decay is a two-body decay and isotropic in the center of mass (cm) system of the pion. This means that inside CORSIKA the direction of the muon is drawn from a uniform distribution and the energy is shared between the muon and the neutrino. Demanding that the total momentum in the cm system adds up to zero, the muon energy is given by [46]:

$$E_{\mu,cm} = \frac{m_{\pi}^{2} + m_{\mu}^{2}}{2m_{\pi}} = 1.039m_{\mu}$$ (3.21)

3.4.4 Kaons

Kaons can decay in a wide variety of states. Table 3.1 shows the most common kaon decays [26]. The kaon decays probabilities are calculated using Quantum Electro Dynamics (QED) and recent accelerator results. The decay of Kaon resonances are treated as well, but are not as common and not as relevant for this work as the normal kaon decay channels.

3.4.5 Charm hadrons

The creation of charm hadrons is not done inside CORSIKA. To treat high energy particles that might create charm particles a separate ‘plugin’ or module is used, such as DPMJET or QGSJET. The charm particles are subsequently transported to the CORSIKA main program in which the charm particles always will decay because of their short lifetime ($\sim 10^{-12}$ s for mesons $\sim 10^{-13}$ s for baryons). The most common charm meson and baryon decay channels are shown in table 3.2.

28
3.5 Hadronic interactions

The hadronic interactions are treated by several different modules depending on energy. If the energy of the primary is above a certain threshold, i.e., 80 GeV, the interactions are treated by one of the high-energy modules, such as QGSJET, DPMJET or SIBYLL of which SIBYLL gives in the presented analyses results that are comparable to QGSJET.

### 3.5.1 The QGSJET module

QGSJET (Quark Gluon String model with JETs) is one of the CORSIKA modules that treats charmed interactions and is an extension of the QGSJET model [39]. QGSJET describes hadronic interactions using super critical Pomeron exchange. Pomerons are force-carrying pseudo-particles proposed to explain the energy behavior of soft hadronic collisions at high energies. The Pomerons are cut following the Abramovskii-Gribov-Kancheli rule and form two strings each. These strings are fragmented by a procedure similar to the Lund algorithm, but with deviating treatment of the momenta at the string ends. Additionally QGSJET includes mini jets to describe the hard interactions which are important at the higher energies. In the case of nucleus-nucleus collisions the participating nucleons are determined geometrically by Glauber calculations, assuming a Gaussian distribution of the nuclear density for the light nuclei with $A \leq 10$ and a Woods-Saxon distribution for the heavier nuclei.

### 3.5.2 The DPMJET module

DPMJET (Dual Parton Model with JET) is based on the two component Dual Parton Model [47] and contains multiple soft chains as well as multiple mini jets. As QGSJET, it relies on the Gribov-Regge theory and the interaction is described by multi-Pomeron exchange. Soft processes are described by a supercritical Pomeron, while for hard processes additionally hard Pomerons are introduced. High mass diffractive events are described by triple Pomerons and Pomeron loop graphs, while low mass diffractive events are modeled outside the Gribov-Regge formalism. Cutting a Pomeron gives two strings, which are fragmented by the JETSET routines according to the Lund algorithm.

Short living secondaries that are not known inside CORSIKA are decayed inside DPMJET. DPMJET also produces charmed hadrons which cannot be treated by CORSIKA. Therefore within the charmed hadrons, the charmed quark is replaced by a strange quark and the modified strange hadrons are tracked by CORSIKA, which treats the interactions and decay from then on.

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### Table 3.2: Most common Charm decay modes and their respective branching ratios [25].

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Ratio (%)</th>
<th>Decay mode</th>
<th>Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^+ + \ldots$</td>
<td>54.0</td>
<td>$D^0 \rightarrow K^+ + \ldots$</td>
<td>53.0</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0 + \ldots$</td>
<td>32.0</td>
<td>$D^0 \rightarrow K^0 + \ldots$</td>
<td>42.0</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^0 + \mu^+ + \nu_\mu$</td>
<td>7.0</td>
<td>$D^0 \rightarrow \bar{K}^0 + \mu^+ + \nu_\mu$</td>
<td>3.2</td>
</tr>
</tbody>
</table>
3. COSMIC RAY SIMULATION FRAMEWORK
4

Lateral Separated Muons

4.1 Introduction

In an attempt to investigate the early developments in cosmic ray showers, an analysis on the IceCube data was performed [48]. This analysis focused on high energy muons (1 TeV), which are produced early in the shower development. High energy muons are generally classified as either conventional or prompt muons. Conventional muons are produced by means of pion and kaon decay. Prompt muons are a result of the decay of particles that contain heavy quarks, which in this analysis are charm quarks. Muons with energies less than 100 TeV are predominantly the result of conventional muons. Above 100 TeV prompt muons are expected to dominate [49], but this effect has not yet been observed [50]. The effect of the two muon fluxes translates to a difference in spectral index, i.e., $dN/dE_\mu \propto E_\mu^{-3.7}$ for conventional muons and $dN/dE_\mu \propto E_\mu^{-2.7}$ for prompt muons.

To discriminate between different phenomenological models this study looked at muons that are laterally separated from the main shower core. A muon with a separation of more than 30 m from the path of the shower core is the result of the transverse momentum ($p_T$) imparted on muon by its parent. Higher transverse momenta, i.e., $p_T \gtrsim 2$ GeV/c, are a result of interactions that can be described in the framework of perturbative Quantum Chromo Dynamics (pQCD). Next-to-leading-order (NLO) pQCD calculations agree well with recent data from particle accelerators, such as the RHIC and the LHC [51].

4.2 Model

To describe high $p_T$ muons, two regions are considered. For $p_T < 2$ GeV/c the interactions cannot be described by pQCD and are called soft interactions. For $p_T > 2$ GeV/c the interactions are called hard interactions and are well described by pQCD. The transition from soft to hard interactions is visible in the $p_T$ spectrum. For soft interactions the spectrum falls exponentially $\propto \exp(-p_T/T)$, with $T \approx 220$ MeV/c for pions [52] and for hard interactions the spectrum falls off following a power law $\propto 1/(1 + p_T/p_0)^n$, with one fit finding $n = 13.0^{+1.0}_{-0.5}$ and $p_0 = 1.9^{+0.2}_{-0.1}$.
4. LATERAL SEPARATED MUONS

GeV/c $^{[53]}$.

To measure the $p_T$ of laterally separated muons a linear relationship between separation and $p_T$ is assumed. Confidence in a linear relationship was strengthened by the MACRO experiment. Their simulations verified the linear relationship, save for a small offset due to multiple scattering of the muons, up to a $p_T$ of 1.2 GeV/c $^{[54]}$, which is below the expected transition to pQCD. The relation between the $p_T$ of the separated muon and the separation distance from the shower core $d_T$ is given by $^{[55, 56]}$:

$$d_T \approx \frac{p_T h c}{E_\mu \cos \theta},$$

(4.1)

where $d_T$ is the perpendicular separation between the muon and the shower core, $h$ is the interaction height of the primary as shown in figure 4.1, $h / \cos \theta$ is the path length of the shower to the ground at a zenith angle $\theta$ and $E_\mu$ is the energy of the muon at creation. Both $\theta$ and $h$ are measured relative to frame of reference of the detector. In this analysis the interaction height where the muon is created and first interaction height of the primary are assumed to be approximately equal and the muon energy at the surface of the Earth is assumed to be a good approximation of the energy at creation. Muons can also separate as a result of the Earth’s magnetic field, but the effect is considered negligible, except for large zenith angles. However, the muons under consideration in this analysis are $> 273$ GeV, which corresponds to a gyro radius of 20,000 km. Another effect not taken into account is multiple scattering of the muon, which is negligible for the energies under consideration. Multiple scattering can be described with a Gaussian distribution around the original direction of propagation, amounting to $\lesssim 10$ meters of lateral separation.

![Figure 4.1](image)

**Figure 4.1:** The interaction height of the primary particles simulated with the DPMJET module as a function of the cosine zenith angle (black). Also shown are distributions for showers with a muons laterally separated more (blue) and less (red) than 135 m.
The 1450 meters of ice above the IceCube detector creates a threshold for the muon energies that make reach the detector. Figure 4.2 shows the zenith angle dependent average and minimum muon energy required to reach the detector. The effect of an approximately exponential increase towards higher zenith angles can clearly be seen.

![Figure 4.2: The distribution of the true energy as a function of the cosine zenith angle as simulated with CORSIKA, using the SIBYLL module for high energies, for muons with the largest separation from the shower core, passing all the quality cuts. Also shown are fits to the minimum and average energy.](image)

The zenith angle distribution also depends on the parent of the muons. At energies of several TeV, the production mechanism of muons is predominantly kaons and pions decaying before they can interact. At higher zenith angles this effect is even stronger because the parents spend more time at higher altitudes where the probability of interacting is even smaller as a result of a lower density. The predicted muon flux is [57]:

\[
\frac{dN}{dE_\mu} \propto \frac{0.14 E_\mu^{-2.7}}{\text{cm}^2 \text{s sr GeV}^{-3.7}} \left[ \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{1150 \text{GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 \text{GeV}}} + \frac{9.1 \times 10^{-6}}{1 + \frac{1.0 E_\mu \cos \theta}{5 \times 10^3 \text{GeV}}} \right],
\]

(4.2)

where the three terms represent the production by pions, kaons and charmed mesons, respectively. Figure 4.3 shows the scaled differential muon rate as a function of cosine zenith for the different components. As can be seen, the fraction of muons from charmed mesons increases towards higher zenith angles.

4.3 Analysis

As previously described in chapters 1 and 2 when a cosmic ray, or primary particle, interacts in the atmosphere, copious amounts of secondary particles are created. The particles that reach the detector, buried under 1400 meters of ice, are predominantly muons. The light tracks that
4. LATERAL SEPARATED MUONS

Figure 4.3: The scaled differential event distribution as a function of the cosine zenith angle for different particle interactions, with 0 being horizontal and 1 being vertical showers. The curves have been scaled to the peak bin and the mean energy of the muons is 2 TeV (±10%).

were created as a result of the muons passing through the detector are observed by the Digital Optical Modules (DOMs) that make up the detector. The observed signals are aggregated into one event when the amount of observed light is above the threshold for Extreme High Energy (EHE) events \[58\]. To obtain two separated tracks from the data, every event was reconstructed using a two track hypothesis, where one track represents the shower core, i.e., the center of the muon bundle, and the second track represents the laterally separated muon (LS muon). The perpendicular distance between the two tracks, at the center of the IceCube detector, is defined as the lateral separation distance \(d_T\). For events that do not contain a LS muon, the second track represents the lateral extent of the CR shower.

In order to reconstruct two separate tracks initially one track is fitted to the data based on the time residuals using a least squares fit. The time residuals indicate the propagation direction of the light wavefront. The ‘simple’ fit is then used to project the hits on a plane perpendicular to the track. The projected hits are sorted, using the k-means clustering algorithm \[59\], into two clusters, i.e., \(k = 2\). The hits are DOMs that detected the Cherenkov light. The k-means algorithm clusters the hits according to the proximity to the mean of each cluster. After assigning all hits to one of the clusters, the mean is recalculated and the hits are reassigned. The process is repeated until convergence is reached. The largest set of hits is assumed to be the muon bundle and is reconstructed with a maximum-likelihood function that accounts for arrival time of the Cherenkov light and the light scattering in the ice \[60\].

The hits that belong to the LS muon can be identified by their time residual relative to the bundle track. Because the LS muon arrives at approximately the same time in the detector as the bundle does, the light from the LS muon is detected earlier than it could have arrived.
4.4 Results

from the bundle track. In this analysis, hits that are recorded 100 ns earlier than the expected light from the bundle track are considered LS muon hits. An additional quality cut was made by demanding that all LS muon hits are at least 90 m away from the bundle track fit, to avoid contamination of the LS muon track. The values were chosen to maximize the number of successfully reconstructed double track events and to minimize the misclassification of hits. Next, the process was iterated to increase the accuracy of the total reconstruction, which was particularly helpful in cases where the clustering algorithm performed poorly due to badly chosen initial means. The resulting accuracy in the angular reconstruction was 4.0° for the bundle tracks and 5.6° for 68% of the events. The separation is measured with a resolution of approximately 30 m, due to the spacing between the DOMs.

In order to remove unwanted background events, such as two coinciding showers, miss-reconstructed single showers and badly reconstructed actual events, certain quality cuts were applied to the data. The effect of each cut was evaluated using CORSIKA simulations in which both the signal and the backgrounds were simulated. To reduce the number of double showers the two reconstructed tracks are required to be within 5° of each other and have a time difference that is smaller than ±450 ns at the point of closest approach at the center of the detector. The limits on angular separation and time difference reduced the number of double showers by a factor of 1500 while reducing the signal only by a factor of 2. Removing single showers was done by demanding that events were not well-constructed by a single track likelihood function. Requiring a high likelihood that events are not single track events reduced the background by a factor of 30 while retaining 40% of the signal. To further improve the signal to background ratio, events with a separation, \( d_T \), of less than 135 m were removed, reducing the background by a factor of 4, while retaining 80% of the signal. At this point the predicted background event rate was 1/30th of the predicted LS muon event rate. To further improve the angular resolution it was demanded that the LS muons hits at least 3 strings and more than 8 DOMs, improving the angular resolution from 7.3° to 5.6°, while removing only 20% of the signal.

4.4 Results

After improving the signal to background ratio from \( 1.20 \pm 0.01 : 1 \) to \( 34 \pm 3 : 1 \), 34,754 data events remained, including 456 double showers predicted by off-time data and 562 ± 90 showers without an LS muon predicted by simulation (SIBYLL). The number of events predicted by simulations depends on the interaction model. DPMJET predicted 27,500 events, QGSJET predicted 57,300 events and SIBYLL predicted 45,200 events. Figure 4.4 compares the data and the three interactions models. The distribution shown in figure 4.4 includes the effect of particle propagation through the ice and the efficiency of the detector. To correct for this, an efficiency for each bin the ratio of simulated events at the surface to the number simulated events after applying all the quality cuts was calculated, using data from all three interaction models. Figure 4.5 shows the corrected data using the calculated ratio.

If a larger separation is the result of a large transverse momentum, the expected distribution
4. LATERAL SEPARATED MUONS

Figure 4.4: The number of events per bin as a function of the LS muon separation after applying all selection criteria for both data and simulation. The off time data shows the differential rate of randomly coinciding showers that passed all cuts.

\[ \frac{\chi^2}{\text{ndf}} = 45 / 21 \]
\[ \text{Prob} = 0.001731 \]
\[ A = 24.15 \pm 0.18 \]
\[ B = -0.04226 \pm 0.00130 \]
\[ C = 7.522 \pm 1.312 \]
\[ n = -10.88 \pm 4.75 \]

Figure 4.5: The corrected data, as it would have been observed at the surface of the Earth, as a function of the LS muon separation. The solid black line shows the full fit of equation (4.3). The red dotted line shows the exponential part of the fit and the blue dashed line shows the power law part of the fit.
would follow an exponential that transitions to a power law at larger separations. The separation
distribution was fitted with the following function:

\[
\frac{dN}{dd_T} = e^{A+Bd_T} + 10^C \left(1 + \frac{d_T}{400 \text{ m}}\right)^n,
\]

(4.3)

where the constants \(A\), \(B\), \(C\) and \(n\) were allowed to vary. Figure 4.5 shows the results of the fit
and the separate contributions of the two terms. The composite shows better agreement than
an exponential function alone with a \(\chi^2/\text{DOF}\) of 45/21 versus 68.6/23 respectively.

The zenith angle dependence of the event rate was also investigated. Figure 4.6 shows the
differential number of events as a function of the cosine of the reconstructed zenith angle. Both
QGSJET and SIBYLL overpredicted the number of events at higher zenith angles and all models
under predict the number of events at lower zenith angles. Overall DPMJET appears to agree
better with the data. Figure 4.7 shows the ratio of simulation to data as a function of cosine
zenith angle. Although DPMJET appears to agree significantly better than the other two models,
a Kolmogorov-Smirnov test showed that none of the models yield a high probability of being
drawn from the same distribution, with DPMJET scoring the highest with \(5 \times 10^{-12}\).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4_6.png}
\caption{The number of events per bin as a function of the cosine zenith angle after applying
al selection criteria for both data and simulation. The off time data shows the differential rate of
randomly coinciding showers that passed all cuts.}
\end{figure}

4.5 Discussion

DPMJET has shown to match the data better at higher zenith angles, where the \(p_T\) is expected
to be slightly higher, however, DPMJET, together with QGSJET and SIBYLL, under predicts the
number of events at low zenith angles, where the \(p_T\) is expected to be slightly higher as well
(see figure 4.8). The three models calculate the \(p_T\) in different ways [39, 61, 62, 63], which
4. LATERAL SEPARATED MUONS

Figure 4.7: The ratio of simulation results to data as a function of the cosine zenith angle of the shower bundle after applying all selection criteria.

might explain the discrepancy. One of the features that stands out is the way charmed particles are treated. SIBYLL does not include charm at all, whereas QGSJET and DPMJET do. DPMJET, however, is the only one of the latter two that treats charmed particles in both soft and hard interactions. A dedicated analysis was performed to investigate the hypothesis that charmed particles are the cause of the better agreement in higher zenith angles, it is described in chapter 5.
Figure 4.8: The minimum and average LS muons transverse momentum as a function of cosine zenith angle for all LS muons that pass all the selection criteria, using equation (4.3) and the interaction height from figure 4.1.
4. LATERAL SEPARATED MUONS
High Transverse Momentum Prompt Muons

5.1 Introduction

As described in chapter 4, the simulation predictions in the Laterally Separated muon (LS muon) analysis did not match the data. The suggested cause of the discrepancy was the difference in charm treatment between QGSJET and DPMJET. The difference may be an explanation for the better agreement of DPMJET with the data. In the analysis presented here, the relative contribution of prompt showers on the lateral separation distribution and transverse momentum distribution was investigated.

Partially the explanation was sought in the relative contributions of kaons, pions and charm mesons to the zenith angle dependent muon flux. Muons with energies above 100 TeV are expected to come predominantly from charm meson decays. pQCD calculations predict that charm meson decays result in a relatively large transverse momentum, i.e., $p_T > 2$ GeV/c. The large $p_T$ would, on average, yield a separation from the shower core that is larger than for conventional muons.

5.2 Model

To calculate the transverse momentum two approaches were used:

$$p_T \approx \frac{E_\mu d_T \cos \theta}{hc}$$  \hspace{1cm} (5.1)

$$p_T \approx \sin(\psi)E_\mu/c$$  \hspace{1cm} (5.2)

where $E_\mu$ is the energy of the LS muon, $\psi$ the opening angle between the bundle track and the LS muon, $d_T$ is the lateral separation, $h$ the production height of the muon, $\theta$ the zenith angle and $c$ the speed of light. The symbol $\psi$ was used for clarity, since it describes a space angle expressed in radians, unlike steradians associated with the space angle $\Omega$. Also, for the track of
the muon bundle, the extrapolated path of the primary particle is assumed. The opening angle \( \psi \) is calculated with the following vector expression:

\[
\psi = \arctan \left( \frac{|\vec{v} \times \vec{v}_p|}{\vec{v} \cdot \vec{v}_p} \right)
\]  

(5.3)

where \( \vec{v} \) and \( \vec{v}_p \) are the direction vectors of the LS muon and the primary particle respectively. Either just the dot or cross product could have been used to calculate the opening angle as well. However, the expected opening angles were small enough to suffer from rounding errors. To ensure non-zero opening angles, the use of both the dot and cross product was chosen. The separation between the two particle trajectories, perpendicular to the trajectory of the primary particle at the observation level, was calculated using the following expression:

\[
d_T = |\vec{v}_p \times (\vec{p}_p - \vec{p})|
\]

(5.4)

with \( \vec{p}_p \) and \( \vec{p} \) the position vectors of the trajectories of the primary and the particle in the observation plane respectively. For \( \vec{p}_p = (0, 0, h_{\text{obs}}) \) and \( \vec{p} = (\sqrt{x^2 + y^2}, 0, h_{\text{obs}}) \) equation (5.4) reduces to \( d_T = r \cos \theta \), with \( r = \sqrt{x^2 + y^2} \), the distance between the track of the extrapolated primary particle and the muon in the observation plane.

In order to use equation (5.2) directly with the available data, an attempt was made to correlate an energy estimate for the simulated events to their real energy. Because the energies of the simulated LS muons fell low energy range (< 1 TeV), energy estimations using the stochastic energy losses [64] were unsuccessful. The energy estimations rely on \( dE/dx \) scaling with the energy of the particle. Low energy muons, however, are almost only ionizing, which is a relatively flat distribution, as shown in figure 3.3. An alternative correlation between the simulated energy and other measurable parameters was sought, but without success.

Without being able to measure the energy of the LS muon, an attempt was made to relate the LS muon separation from the bundle track to the transverse momentum of the particle, while also distinguishing between prompt and conventional showers. To determine whether a cosmic ray shower muon is prompt or conventional, the history of the particles was investigated. Because the latest version of CORSIKA does not save the history of the particles, small alterations to the source code were made to obtain information about the parents and grandparents of the particles. Figure 5.1 shows the information known during the analysis. Note that although both a parent and grandparent are shown in figure 5.1 a muon can have a range from one to many ancestors, but only the last two ancestors are kept for further analysis.

As described in chapter 3 CORSIKA can simulate cosmic ray showers for two different geometries: flat and curved. The first part of the analysis was performed using the flat Earth approximation and only uses showers simulated up to a zenith angle of 60°. The flat Earth model was used to obtain confidence in the analysis and gain insight about the difference in the prompt muon flux between the two interaction models, i.e., DPMJET and QGSJET. One of the key pieces of information to obtain was the zenith angle distribution of the different types of (grand-)parents, pions, kaons and charmed mesons. In later studies the geometry was changed.
5.2 Model

Figure 5.1: The CR showers simulated with CORSIKA can save the partial history of a particle. The information known of primary particle, the muon, its parent and grandparent are the 3D location and direction at the end of their tracks, which for the muon is at the observation level. Interaction that take place before between the primary interaction and the end of the grand parent’s life are not known, but are in general not necessary. Note that a muon can have anywhere between one and many parents, but only the last two parents are registered.

To the curved Earth model and the zenith angle range was expanded to 89.99°. Throughout this entire analysis all simulations were performed using the Hörandel spectrum, which describes, compared to recent measurements, both the spectrum and composition of cosmic ray primaries reasonably well [65]. The energy range over which the simulations were performed is $10^4 \leq E_p \leq 10^8$ GeV with a secondary particle minimum energy cutoff at 273 GeV. The 273 GeV cutoff is used in all standard IceCube simulations and represents the minimum energy a muon requires to travel from the top of the ice to the top of the detector 1450 m lower, plus a safety factor in order not to over-estimate the rate.

In order to compare the differential rate found in simulation with the data, the life time of the simulations was calculated. The following expression was used to determine the lifetime of the simulations:

$$T_{\text{lifetime}} = \frac{N}{\mathcal{F}A},$$

(5.5)

with $N$ the number of simulated showers, $A$ the area sum of the detector and $\mathcal{F}$ the fluxsum, given by CORSIKA. The fluxsum is a constant given by CORSIKA that represents the expected flux, depending on the spectrum and angle of acceptance used in the simulation. The area sum is the cross sectional area of the detector integrated over the angle of acceptance. The values used for simulation with the Hörandel spectrum, ranging in zenith angle from 0-90 degrees is $1/\mathcal{F}A = 1.378 \cdot 10^{-5}$ s. To put into perspective, simulating a year of lifetime with a full acceptance of 0-90 degrees would require $2.3 \cdot 10^{12}$ showers.
5. HIGH TRANSVERSE MOMENTUM PROMPT MUONS

5.3 Results

5.3.1 Model verification

At the end of the Lateral Separation analysis, described in chapter 4, a possible cause of the large discrepancy between the zenith angle dependent predictions of QGSJET and DPMJET was the treatment of charm interactions. Therefore, the first step was to investigate the prompt muon flux from both DPMJET and QGSJET. Figure 5.2 shows the prompt muon flux obtained from the two models. For completion the non-prompt flux has been considered throughout this analysis as well, for it may be that the discrepancy can be explained in the relative abundance of pions and kaons in either of the two models. Figure 5.3 shows the simulated non-prompt flux, separated according to the parent type of the muon.

As can been seen in figure 5.2, the prompt flux from DPMJET is significantly larger, i.e., 12 times, which strengthened the believe that the charm treatment was indeed the dominant factor involved. It is clear that there is a significant difference in muon flux predictions from the two models, with DPMJET best matching the predictions from Thunman [66] for the non-prompt flux, based on pQCD calculations. For clarity, figure 5.4 shows the ratio between the two models for the non-prompt muon flux, split up between kaon and pion parents.

5.3.2 Lateral separation and transverse momentum

Preliminary investigations showed that charm interactions may have been the source of the difference between QGSJET and DPMJET, and possibly between DPMJET and the data as well. Because the DPMJET predictions matched the data best, the choice was mad to use only DPMJET
5.3 Results

Figure 5.3: The non-prompt, or conventional, flux as generated by CORSIKA simulations, using DPMJET (blue) and QGSJET (red) as interaction model. The black solid line shows the non-prompt flux predicted by Thunman et al. [66]. The contributions of pions (dotted lines) and kaons (dashed lines) are separately shown as well.

Figure 5.4: The ratio between the CORSIKA interaction models DPMJET and QGSJET of the simulated muon flux fraction from pions (blue) and kaons (red).
5. HIGH TRANSVERSE MOMENTUM PROMPT MUONS

\[
A | B \, [1/\text{m}] | C | n | \chi^2/\text{DOF}
\]

| Lateral Separated data | 24.2 ± 0.2 | -0.042 ± 0.001 | 8 ± 1 | -11 ± 5 | 45/21 |
| DPMJET simulation | 10.3 ± 0.4 | -0.026 ± 0.005 | -3 ± 2 | 6 ± 4 | 39790/44 |

Table 5.1: The fitted parameters of equation (4.3) to the simulated data from DPMJET compared to the data from the Lateral Separated muon analysis.

for further investigation, unless otherwise noted. To make sure that the relative abundance of pions and kaons was not overlooked, all distributions shown in this section have been split up according to the parent of the muon that is found at observation height.

The muon flux, as observed at the surface from DPMJET, is shown in figure 5.6. The spectrum of QGSJET is very similar, albeit lower in rate for prompt muons. The default cutoff of 273 GeV is here, and from here onwards, replaced by a fit to the minimum muon energy found in the LS muon analysis, i.e., the muon with the minimum energy in each zenith angle bin, after all cuts were made. The results of the minimum energy fit are shown in figure 5.5. Figure 5.7 shows the differential flux as a function of the lateral separation.

![Figure 5.5](image)

Figure 5.5: The minimum energy a muon requires to reach the top of the detector under the ice as a function of the cosine zenith angle. The solid line shows the minimum energy for all muons and the dotted line shows the minimum energy for the lateral separated muon.

The total distribution shown in 5.7, representing the raw DPMJET data, was fitted with equation (4.3), with the resulting parameters shown in table 5.1 together with the fit results obtained in the Lateral Separation (LS) analysis. The results of the fit correspond badly to the fit of the corrected data. A fit of only the exponential part of the expression yielded better results, indicating that the bad overall fit was a result of low statistics. Figure 5.7 shows, however, indications of a flattening of the spectrum for larger separations.

The prime question from the LS analysis was the prompt fraction of the differential LS
5.3 Results

**Figure 5.6:** The differential muon rate at the observation level as simulated by CORSIKA using the DPMJET interaction module. The different lines represent the various parents, i.e., charmed mesons (red), kaons (green) and pions (blue), that created the observed muons. The black solid line shows the overall spectrum.

**Figure 5.7:** The differential lateral separated (LS) muon flux as a function of the separation distance (black open symbols). The fractional contributions to the LS muon flux from the different parents are shown as well, for pions (blue), kaons (green) and charmed mesons (red). All muons are above the zenith angle dependent minimum energy required to reach the top of the detector under the ice (see figure 5.5).
muon flux as a function of the cosine zenith angle. Figure 5.8 shows the differential muon flux for the LS muon as function of the cosine zenith angle. It appears that the muon flux from charmed mesons and kaons becomes relatively more dominant at higher zenith angles. Because the discrepancy between the data and the simulations was in the cosine zenith distribution, for both models the relative fraction of muons created for each parent was calculated and is shown in figure 5.9. Note that the fraction of kaons goes up and the fraction of pions goes down with increasing zenith angle for dpmjet, with the opposite being true for qgsjet. Although the prompt muon statistics for qgsjet are significantly lower than for dpmjet, it appears that the fraction of prompt muons stays constant over zenith angle for both models.

Figure 5.8: The differential muon flux as a function of the cosine zenith angle. The black solid line shows the overall flux, whereas the other solid lines show the fractional muon flux for different parents, i.e., pions (blue), kaons (green) and charmed mesons (red).

In order to investigate the relationship between lateral separation and the transverse momentum ($p_T$), the $p_T$ distribution was calculated using equation (5.2). An attempt was made to fit the distribution with the following expression:

$$\frac{dN}{dp_T} = e^{ap_T+b} + W \left( 1 + \frac{p_T}{p_{T,0}} \right)^{-n},$$

which, ignoring the exponential contribution, resulted in $W = 1, p_{T,0} = 2.9$ GeV and $n = 0.4$, not matching the predicted values $W = 5 \cdot 10^5, p_{T,0} = 1.9$ GeV and $n = 13.0$. Figure 5.10 shows the transverse momentum distribution and figure 5.11 shows the fractions of muons that result for a certain parent as a function of $p_T$. Note that the fraction of prompt muons increases for $p_T < 3$ GeV/c at the dispense of muons from pion decay.

Figure 5.12 shows the relationship between the transverse momentum, as calculated per equation (5.2), and the LS muon separation, calculated using equation (5.4). It can be seen that the linear relationship between $p_T$ and separation, $d_T$, holds. As expected, the average
5.3 Results

**Figure 5.9:** The fractions of the muon flux made up by various parents, as simulated by CORSIKA with the interactions models DPMJET (closed shapes) and QGSJET (open shapes), as a function of the cosine zenith angle.

**Figure 5.10:** The differential muon flux as a function of the transverse momentum, as simulated by CORSIKA using the DPMJET interaction module. The black solid line shows the overall flux, whereas the other solid lines show the fractional muon flux for different parents, i.e., pions (blue), kaons (green) and charmed mesons (red).
5. HIGH TRANSVERSE MOMENTUM PROMPT MUONS

Figure 5.11: The fraction of the muon flux resulting from either pions (blue), kaons (green) or charm mesons (red) as a function of the transverse momentum, as simulated by CORSIKA using the DPMJET interaction module.

\[ p_T \text{ of only the LS muons is higher than the average for all muons. Both the set of all muons and the set of LS muons were fitted with a linear function. The results for all muons yielded: } p_T = (0.71 \pm 0.03) \text{ GeV/c} + (7.1 \pm 0.2) \cdot 10^{-3} \, d_T \text{ and the result for LS muons yielded: } p_T = (0.70 \pm 0.09) \text{ GeV/c} + (10.9 \pm 0.7) \cdot 10^{-3} \, d_T. \text{ The results of the LS muons agrees well with the LS muon analysis performed by MACRO, which showed an increase of } p_T \simeq 0.01 \, d_T. \]

5.4 Discussion

The hypothesis that the discrepancy found in the Lateral Separated muon analysis, where the data and the simulation prediction do not match in the zenith angle distribution, was caused by the treatment of charm in the various models was found to be inconclusive. Both DPMJET and QGSJET treat charm in their models and differ greatly, which is apparent in the difference in prompt muon flux. The difference in relative composition of kaons and pions between the two models is a more likely explanation for why DPMJET agrees better with the data, because the relative fractions of kaon and pion parents diverges towards larger zenith angles, which is the region of largest discrepancy.
Figure 5.12: The transverse momentum of the lateral separated muon, $p_T$, as a function of the lateral separation, $d_T$. All muons are above the zenith angle dependent minimum energy required to reach the top of the detector under the ice (see figure 5.5). The black open symbols show the relation for all muons in a simulated shower, whereas the blue closed symbols show the relation for only the LS muon in each simulated shower.
5. HIGH TRANSVERSE MOMENTUM PROMPT MUONS


6

Coincident Up-going Neutrinos from a Single Cosmic Ray Shower

6.1 Introduction

The IceCube detector is in principal a neutrino detector. To guarantee a nearly pure neutrino signal, IceCube uses the Earth as a shield against unwanted muons that resulted from down-going, i.e., $\theta < 90^\circ$, cosmic rays, resulting in a neutrino signal in the range $90^\circ \leq \theta \leq 180^\circ$. The most common muon tracks, resulting from neutrino interactions, are single tracks, e.g., from cosmic rays or the sun [67]. However, an observation of double, parallel tracks in IceCube would have significant implications. This signature could be an indication of a supersymmetric (SUSY) stau decay near the detector, which would point to ‘new physics’. In the SUSY model, a neutrino can produce a pair of SUSY particles, which, in turn, decay into pairs of next-to-lightest SUSY particles. These particles would show up in the IceCube detector as two nearly parallel tracks, due to their long lifetime in the order of $\mu s$, which gives the particles enough time to significantly separate from each other [68].

When a cosmic ray neutrino is detected in IceCube it is most likely the only track of the event, due to the small probability of being detected, which in turn is a result of the small neutrino cross section. When two cosmic ray neutrino tracks are detected, the most probable origin is two different cosmic ray showers, due to the large angle of acceptance. There is, however, as small chance that two neutrinos are detected from a single cosmic ray shower, which would show up in the detector as two parallel tracks. The signal for two parallel tracks, as a result of two neutrinos interacting near the detector, is the only signal that is likely to mimic the stau signal.

An on-going search is taking place in the IceCube collaboration to detect the characteristic up-going parallel tracks of a stau decay. The predicted rate of detecting a stau decay with IceCube is 0.01 - 1 per year, decreasing with increasing mass of the stau particle [68]. The low probability of detecting a stau decay prompted the idea that cosmic rays might provide a significant background to the stau signal. This analysis investigates the expected event rate of...
6. COINCIDENT UP-GOING NEUTRINOS FROM A SINGLE COSMIC RAY SHOWER

parallel tracks in the detector resulting from a single cosmic ray event.

### 6.2 Model

For this investigation down-going cosmic ray showers were simulated with CORSIKA, albeit slightly altered. The altered simulation returns the muon tracks and energies with two more significant digits than the unaltered simulation would have. The increase in precision was necessary to guarantee non-zero openings angles between the two tracks. The resulting simulation files describe all the particles that have an energy above 100 GeV and have reached the surface of the Earth. The surface of the Earth is not always at sea level, which has prompted the use of the term observation level. The observation level van be placed arbitrarily high above sea level, but is positioned in the case of IceCube at 2.834 km, i.e., the top of the ice shelf. In order to obtain up-going shower simulations, the muon tracks in the output were taken and extrapolated to the other side of the Earth. The location of the detector then was translated along the initial path of the primary particle. Figure 6.1 shows schematically what was done and the relevant parameters involved.

As shown figure 6.1 the most relevant parameters are $\theta$, the angle with zenith, $\psi$, the openings angle between two particles and $D$, the perpendicular distance between the two particles when extrapolated to the other side of the Earth. The distance $D$ and path length $L$ can be calculated with the following expressions:

\[
D = \tan \psi (2R_{\text{obs}} \cos \theta - r \sin \theta) + r \cos \theta \quad (6.1)
\]

\[
L = 2R_{\text{obs}} \cos \theta, \quad (6.2)
\]

where $r$ is the distance between the two particles measured in the plane of the observation level and $R_{\text{obs}}$ is the radius from the core of the Earth to the observation level. In the analysis a limit was placed on $D = 1000$ m, because of the size of the detector, where the shape of the detector is approximated with a sphere. Due to the limited diameter at the detector and constant starting point of the simulations, i.e., 112.8 km above sea level, the openings angle $\psi$ is bounded. Given a separation of particles at the observation level, the initial openings angle could never have been smaller than $\psi_{\text{min}}$, whereas the maximum separation at the other side of the Earth sets an upper bound $\psi_{\text{max}}$. The corresponding equations are:

\[
\tan \psi_{\text{min}} = \frac{r \cos \theta}{\sqrt{R_{\text{atm}}^2 - R_{\text{obs}}^2 \sin^2 \theta - R_{\text{obs}} \cos \theta + r \sin \theta}} \quad (6.3)
\]

\[
\tan \psi_{\text{max}} = \frac{D_{\text{max}} - r \cos \theta}{2R_{\text{obs}} \cos \theta - r \sin \theta}, \quad (6.4)
\]

where $R_{\text{atm}}$ is the radius from the core of the Earth to the atmosphere. Figure 6.2 shows a 2D contour plot of the required value for $\psi$ as a function of $\log_{10} D_0$ and $\cos \theta$, where $D_0 = r \cos \theta$, the perpendicular distance between the two tracks at the observation level.
Figure 6.1: A schematic representation of the simulation approach: Standard down-going simulations are created and subsequently extrapolated to the other side of the Earth. Here $\theta$ is the zenith angle, i.e., the angle between the track and the surface normal, $\psi$ the openings angle between the neutrinos, $D$ the perpendicular distance between the two neutrinos after extrapolating their paths, $R_{\text{obs}}$ and $R_{\text{atm}}$ the distance from the Earth's core to the observation level and the edge of the atmosphere respectively and $L$ the extrapolated path length through the Earth.
Figure 6.2: Plotted is the 2D field where the openings angle $\psi$ is allowed according to equation (6.3) and (6.4). The vertical axis describes the perpendicular distance between two particles at the observation level, i.e., the height at which the simulation writes out the particle data. The horizontal axis is in cosine zenith angle, with 0 being horizontal and 1 being vertical incoming neutrino pairs.
6.2 Model

When the trajectories of the particles, i.e., neutrinos, are extrapolated to the other side of the world, all particles are paired up with one another and the distance $D$ is calculated. When the distance is less than $D_{\text{max}} = 1000$ m, for each of the two neutrinos the probability of becoming a muon, and hence being detected, is calculated. A maximum separation of 1000 m was chosen because it is the largest separation that will fit in the detector, using $R_{\text{max}} = 500$ m and assuming an ideal spherical detector. The probability of a neutrino undergoing a charged current interaction, and hence creating a muon, is given by [69]:

$$P_i \equiv P(\text{detection}|E_{\nu i}) = \begin{cases} 1.3 \times 10^{-6} \left( \frac{E_{\nu}}{\text{TeV}} \right)^{2.2} & \text{if } E_{\nu} \leq 1 \text{ TeV} \\ 1.3 \times 10^{-6} \left( \frac{E_{\nu}}{\text{TeV}} \right)^{0.8} & \text{if } E_{\nu} > 1 \text{ TeV} \\ 0 & \text{if } D > D_{\text{max}} \end{cases}$$  \quad (6.5)

where $E_{\nu}$ is the energy of the neutrino. It is assumed that when a muon is created it will be detected. Each neutrino out of all neutrinos created has an individual probability of being detected. The probability of any two neutrinos being detected, it was assumed that the probability of detection follows a binomial distribution with a non-constant probability. The number of successful detections was set to two, i.e., $X = 2$. The probability to observe one specific pair of neutrinos is given as the product of the individual probabilities $P_i$.

$$P_{ij} \equiv P_i P_j.$$  \quad (6.6)

Since the probabilities of observing one specific pair is of the order of $10^{-12}$, and thus the probability of not observing any other pair approximates unity, it suffices to sum up all the possible pairs to obtain the probability of observing a single pair from a single cosmic ray shower, given the primary energy $E_p$:

$$P(\text{detection}|E_p) = \sum_{i=0}^{N-1} \sum_{j=i+1}^{N} P_{ij},$$  \quad (6.7)

with $N$ the total number of pairs with a distance $D \leq D_{\text{max}}$. Weighting the probability as a function of the primary energy with the cosmic ray flux predictions $\Phi(E_p)$, the angular acceptance of the detector $\Omega$ and effective area of the detector $A$ results in the following expression for the expected event rate in the detector:

$$\text{Rate} = A \Omega \int_{10^2}^{10^8} \Phi(E_p) P(\text{detection}|E_p) dE_p \quad [s^{-1}]$$ \quad (6.8)

with the integration limits in GeV. The flux $\Phi(E_p)$ for primary energies above 100 GeV is given by [70]:

$$\Phi(E_p) = \begin{cases} 1.8 \cdot 10^4 (E_p/\text{GeV})^{-2.7} & E_p < 10^6 \text{ GeV} \\ 1.1 \cdot 10^6 (E_p/\text{GeV})^{-3.0} & E_p > 10^6 \text{ GeV} \end{cases} \quad [(s \text{ sr m}^2 \text{ GeV})^{-1}].$$  \quad (6.9)

Unless mentioned otherwise, the value of the effective area and the acceptance are taken as $A = \frac{1}{4}D_{\text{max}}^2$ and $\Omega = 2\pi$ respectively.
6. COINCIDENT UP-GOING NEUTRINOS FROM A SINGLE COSMIC RAY SHOWER

The resulting rate is an upper bound because absorption of the neutrinos by the Earth has been ignored, which is expected to be a small effect. Another effect that reduces the final rate is the limited amount of detector that can be hit by the second particle given that the first particle hits the detector. The probability is given by:

\[
P(\text{detection}_2|\text{detection}_1) = \frac{4}{D_{\text{max}}^2 R_{\text{max}}^2} \int_0^{D_{\text{max}}} \int_0^{R_{\text{max}}} P(\text{detection}_2|\text{detection}_1, d', r') r'dr'dd'\tag{6.10}
\]

where \(d\) is the perpendicular distance between the particles and \(r\) is the radial distance of the first particle to the center of the detector. \(P(\text{detection}_2|\text{detection}_1)(d, r)\) is given by:

\[
P(\text{detection}_2|\text{detection}_1, d', r') = \frac{1}{\pi} \arctan\left(\frac{\sqrt{4r^2 R_{\text{max}}^2 - (R_{\text{max}}^2 - d^2 + r^2)^2}}{r^2 - R_{\text{max}}^2 + d^2}\right) \tag{6.11}
\]

\[
= 1 \quad \text{if} \quad r + d < R_{\text{max}} \tag{6.12}
\]

\[
= 0 \quad \text{if} \quad d - r > R_{\text{max}} \tag{6.13}
\]

Numerically integrating the function, using \(D_{\text{max}} = 1000\) m and \(R_{\text{max}} = 500\) m, yields a correction factor of 0.250, assuming an uniform probability of the second particle being found around the first particle. Figure 6.3 shows the probability of detection the second particle, given the separation between the particles.

![Figure 6.3](image)

**Figure 6.3:** The probability of detecting a pair of particles in a detector of size \(R_{\text{max}} = 1000\) m, given the detection of one of the particles and their separation, as a function of the perpendicular separation between the particles at the detector.

The simulations that were run for this analysis consisted of four different models: DPMJET, once with Protons and once with Iron, and QGSJET, once with Protons and once with Iron. All
four simulations used a $dN/dE_p \sim E_p^{-1}$ spectrum to obtain enough statistics over the entire energy range: $10^2 \leq E_p \leq 10^8$ GeV. Figure 6.4 shows the simulated spectrum, which has the spectral index $dN/dE_p \propto E_p^{-1}$, resulting in approximately equal statistics for each energy bin. Due to lengthy simulations required of energies above $10^7$ GeV, the number of simulations were limited to 100,000. Figure 6.5 shows the simulated angular distribution. To avoid confusion, the distributions that depend on the zenith angle $\theta$ are plotted as a function of $\cos \theta$, which removes the influence of an increasing space angle at higher zenith angles. The deviations from a flat distribution in $\cos \theta$ are a result of atmospheric effects taken into account by CORSIKA for vertical events, together with CORSIKA favoring tracks that are at least $1^\circ$ above the horizon, due to round off problems that may occur in later trigonometry calculations for horizontal events.

![Figure 6.4: The primary energy spectrum generated by CORSIKA. The horizontal axis shows the logarithmic energy of the primary particle and the vertical axis shows the number of simulated events falling in each bin. The spectral index of the simulations is $dN/dE_p \propto E_p^{-1}$. The total number of simulations is 100,000.](image)

### 6.3 Results

The first step in calculating the expected event rate was to determine the probability $P(\text{detection}|E_p)$ as a function of $E_p$, using equation (6.7). Running through all the simulated showers, for each shower all the possibilities were summed up, according to equation (6.7). Figure 6.6 shows the probability of detecting a neutrino pair from a single cosmic ray shower as a function of the primary energy, using DPMJET and Proton primary particles. The distribution was fitted with
6. COINCIDENT UP-GOING NEUTRINOS FROM A SINGLE COSMIC RAY SHOWER

Figure 6.5: The primary zenith angle spectrum generated by CORSIKA. The horizontal axis shows the normal component of the zenith angle, i.e., $\cos \theta$, of the primary particle and the vertical axis shows the number of simulated events falling in each bin. The total number of simulations is 100,000.

Table 6.1: The fitted parameters of equation (6.14) for both interaction models, i.e., QGSJET and DPMJET, and for both types of primary particles, i.e., Protons and Iron.

<table>
<thead>
<tr>
<th></th>
<th>QGSJET</th>
<th></th>
<th></th>
<th>DPMJET</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_0 \cdot 10^{-20}$</td>
<td>$E_0$ [TeV]</td>
<td>$w$</td>
<td>$P_0 \cdot 10^{-20}$</td>
<td>$E_0$ [TeV]</td>
</tr>
<tr>
<td>Protons</td>
<td>2.570</td>
<td>1.483</td>
<td>31.77</td>
<td>3.821</td>
<td>1.700</td>
</tr>
<tr>
<td>Iron</td>
<td>4.564</td>
<td>29.40</td>
<td>50.18</td>
<td>31.58</td>
<td>29.51</td>
</tr>
</tbody>
</table>

$y = \sqrt{w(x - x_0)} + y_0$ in double log space. The resulting expression in linear space is:

$$P(\text{detection}|E_p) = P_0 10^{w \log_{10}(E_p/E_0)},$$  \hspace{1cm} (6.14)

where $E_0$ is the minimum primary energy required to form neutrino pairs, $P_0$ the probability at $E_p = E_0$ and $w$ the weight or slope of the curve. The results of the fit for all four situation are given in table 6.1.

The event rate distribution was calculated using equation (6.8), weighting the probability with the expected cosmic ray flux, $\Phi(E_p)$. Figure 6.7 shows the predicted differential event rate as a function of the primary energy, using QGSJET and Proton primaries. The expression that correspond to figure 6.7 is:

$$\frac{dN}{dE_p} = A \Omega \Phi(E_p) P(\text{detection}|E_p) \hspace{1cm} [\text{s GeV}^{-1}],$$  \hspace{1cm} (6.15)

which is equivalent to equation (6.8) in differential form. The distributions peaks around 30 TeV.
and signifies a tradeoff between several influences: the cosmic ray flux decreases with increasing primary energy, the number of neutrinos created increases with increasing primary energy, the detection cross-section of neutrinos increases with increasing neutrino energy, and the average opening angle decreases with increasing forward momentum, i.e., the primary energy.

The final rate was calculated by numerically integrating equation (6.15), using the Dormand-Prince integration method [71] together with the fit results obtained earlier. Table 6.2 shows the final rates for all four situations under consideration. Although QGSJET produces on average 10% more neutrinos per shower for both Protons and Iron primaries, most of these neutrinos are of low energy, aiding little to the overall probabilities.

The dependency on the initial zenith angle of the differential event rate was investigated as well. Figure 6.8 shows the differential event rate as a function of cosine zenith. Most of the events are coming from the region $0 < \cos \theta \lesssim 0.25$, or $75^\circ \lesssim \theta < 90^\circ$. The dominance of events coming from close to the horizon was expected, since the path length $L$ rapidly decreases with increasing zenith angle. The path length between 75 and 89 degrees varies from 3300 km down to 220 km respectively, which gives the pairs less time to separate. However, the
6. COINCIDENT UP-GOING NEUTRINOS FROM A SINGLE COSMIC RAY SHOWER

Figure 6.7: The differential event rate as detected by IceCube as a function of the primary energy.

amount of atmosphere transversed by particles coming from near the horizon is large enough to avoid particles having not enough separation to be discerned. The slight downturn shown at \( \cos \theta > 0.8 \) can be explained by the initial spectrum, shown in figure 6.5.

The size restriction of the detector also plays a significant role in the expected event rate. To quantify the effect of increasing the detector the parameter \( D_{\text{max}} \) was left unrestricted and the distance \( D \) was calculated and binned. It was necessary to bin the values for \( D \) immediately due to the large amount of particles in high energy showers. The number of neutrinos in a shower grows following a power law as function of the primary energy and the number of combinations grows \( \propto n_\nu^2 \). Figure 6.9 shows the effect of increasing the detector size on the expected rate of detecting a neutrino pair in a detector of size \( D \). Naively, assuming uniformly distributed neutrinos, a power law was expected here, but the number of neutrinos at large transverse momentum drops off significantly.

6.4 Discussion

The analysis of the coincident up-going neutrino pairs has yielded insight in the possibilities of detecting such an event with IceCube, and has demonstrated that these events are a significant contribution to the background in searches for stau decays in the higher mass region, i.e, \( m_{\tau} \gtrsim 300 \text{ GeV}/c^2 \). It has also become apparent that both the model and the primary particle species are of limited influence on the predicted rate, with a 5-10% spread.

It is clear that IceCube is located on the most sensitive part of the detector size curve, where a small increase would yield a large change in the rate. For even larger detectors, e.g.
Figure 6.8: The differential event rate as detected by IceCube as a function of cosine zenith, i.e., the normal component of the zenith angle.

Figure 6.9: The predicted event rate in a detector with a diameter of $D_{max}$. 
6. COINCIDENT UP-GOING NEUTRINOS FROM A SINGLE COSMIC RAY SHOWER

KM3NET, which has a proposed detector volume of 6 km$^3$ [72], the expected rate would be approximately 0.8 ± 0.1 events per year, assuming a spherical detector with a diameter of 2.5 km. The increased detector volume makes the detector sensitive to lower zenith angles and larger openings angles. It should be noted, however, that the increase in detector volume is almost always a tradeoff with energy sensitivity, which would eliminate the lower part of the differential event spectrum. Although, as demonstrated, an energy sensitivity of 1.5 TeV and higher is sufficient.

The expected event rate of double up-going neutrinos in IceCube is, assuming an average of the two models, 0.069 ± 0.001 per year or once every 14.5 ± 0.2 years for Proton primaries and 0.060 ± 0.005 per year or once every 16.6 ± 1.3 years for Iron primaries. The actual detection rate may be lower, due to absorption in the Earth, although, this is probably a small effect since most pairs come from within 15 degrees below the horizon where the amount of Earth transversed is relatively small.
Conclusion

The analyses presented in this work breaks down into two parts: Lateral Separated muons (LS muons) and their transverse momentum ($p_T$), and coincident up-going neutrino pairs. The common denominator of the analyses is separated muon tracks in IceCube.

The high $p_T$ analysis showed that the discrepancy found in the LS muons analysis can not be explained by the relative abundance of prompt muons. Prompt muons tend to represent a higher fraction of the total muon flux at zenith angles that are close to the horizon, but do not dominate in the near vertical regime. The analysis also showed that the relative fraction of prompt muons does not go up with increasing $p_T$, which was not expected. Given that for larger muon energies prompt muons start to dominate, it was expected that this would translate to a dominance of prompt muons at larger $p_T$. The difference in LS muon predictions from QGSJET and DPMJET is possibly a result of the difference in relative abundance of kaons and pions. It was found, however, that DPMJET shows a prompt muon flux 12 times larger than QGSJET. The difference is a result of DPMJET treating charm mesons in both soft and hard interactions, whereas QGSJET only takes charm mesons into account in hard interactions.

Further research in this area would benefit from updated extrapolations of the parton distributions, using recent accelerator results, and treatment of heavier quarks, such as bottom quarks. Results from the Relativistic Heavy Ion Collider at Fermilab show that bottom quarks contribute more than 30% of the prompt leptons with a $p_T > 2$ GeV/c in proton-proton collisions at a center of mass energy of 200 GeV [73].

The coincident up-going neutrino analysis showed that the event rate in IceCube is a significant background in the search stau decays. The analysis showed an expected rate of 0.069±0.001 per year, or once every 14.5 ± 0.2 years, for Proton primaries and similar for Iron primaries. From the analysis can be concluded that a measurement of the rate is unlikely to tell us more about the composition. The analysis also showed that a small increase in detector size, compared to IceCube, would significantly increase the sensitivity to coincident up-going neutrinos from a single source.

Further research in this area might benefit from including the omitted influences in the
7. CONCLUSION

simulation: Neutrino absorption in the Earth, energy dependent effective area of the detector or an actual full detector event simulation. Including these effects will alter the final rate. Absorption will lower the final rate, but the detection probability of the muon was conservative with regard to low energy muons, which might balance out the absorption.
List of Figures

1.1 Victor Hess and his balloon in 2012, equipped with a radiation measurement apparatus. ................................................................. 2
1.2 The cosmic ray spectrum. Image courtesy of William F. Hanlon, University of Utah and [17] ................................................................. 4
1.3 A schematic representation of a liquid scintillator detector ................................................................. 5
1.4 A schematic representation of the HiRes detector. Each site can only determine the plane of the trajectory. Intersection of the two observed planes results in a measurement of the direction of the cosmic ray shower. ................................................................. 6
1.5 A schematic representation of a Cherenkov detector. The spheres are Digital Optical Modules housing a PMT and processing electronics. The blue cone is the Cherenkov light emitted by the medium. ................................................................. 7
1.6 A schematic representation of a cosmic ray shower. On the left a conventional CR shower is shown, where primarily Kaons and Pions are created on the first interaction. On the right a prompt CR shower is shown, where the first interaction creates a meson containing heavier quarks, i.e., charm and heavier. Prompt CRs are predicted to dominate above 100 TeV and conventional CRs below 100 TeV. ................................................................. 8
1.7 Lines show where the probability of decay and of interaction are equal, for different mesons. Image courtesy of Dr. Dieter Heck [25] ................................................................. 9

2.1 The optical scattering and absorption of the ice at the location of AMANDA and IceCube. The depth dependence and the wavelength dependence for the effective scattering coefficient (left) and for absorptivity are (right) shown as shaded surfaces, with the contribution to scattering due to air bubble in the ice and the pure ice contribution to absorption are superimposed. The dashed lines at 2300 m show the wavelength dependences: a power law due to dust for scattering and a sum of two components (a power law due to dust and an exponential due to ice) for absorption. The dashed line for scattering at 1100 m shows how scattering on bubbles is independent of wavelength. Image courtesy of [28] ................................................................. 14
LIST OF FIGURES

2.2 The IceCube detector with its predecessor AMANDA II shown as well. 15
2.3 A schematic drawing of a charged particle emitting Cherenkov radiation, depicted by the blue arrows. The angle $\theta$ is given by equation (2.1). The solid blue line shows the distance light travels in a medium with refraction index $n$ in time $t$. The solid red line shows the distance the particle travels in the same time $t$ with relative velocity $\beta$. The gray dashed circles are the wave fronts originating from past moments, when the particle was at the position that lays in the centre of the circle. 16
2.4 A schematic drawing of a Digital Optical Module used in the IceCube detector. 60 DOMs are attached to one cable forming one measurement string. IceCube consists of 86 strings in total. 17
2.5 IceCube event displays for (top) a muon or muon bundle IC40, a simulated $\nu_e$ (middle) and a simulated $\nu_\tau$ (bottom). Each point is from a single hit DOM and the size of the circles indicates amount of light detected. The color indicates the relative timing, from red (earliest) to blue (latest). From [33]. 19
2.6 IceCube event display of a muon bundle (wide stroke of lit DOMs) and a laterally separated, high $p_T$, muon (dimly lit stroke of DOMs). The red solid lines are the results of a line fit for the tracks. 20
3.1 The different slant depths in kilometers as a function of zenith angle, using a flat Earth model (red) and a curved Earth model (blue). 22
3.2 A schematic drawing of the parameters involved in particle tracking inside the atmosphere. In both geometries $h$ is the height above the surface, $\theta$ the angle with local zenith, $L$ the track length of the particle and $r$ the distance along the surface of the Earth. In the curved geometry (right) the parameters are different in the frame of reference of the detector, opposed to the flat approximation (left). In the curved geometry $\theta_{app}$ is the apparent zenith angle and $h_{app}$ the apparent height as seen from the detector. To calculate the apparent value, in addition to the other parameters, the radius of the Earth $R_E$ is used and the openings angle with zenith measured at the Earth’s core $\theta_E$ is calculated. For both geometries $h_{obs}$ is the height of the observation plane measured from sea level and $h_{atm}$ the height of the atmosphere, here 112.8 km. 23
3.3 The energy loss of muons in air as a function of its Lorentz factor. Note the separate contributions of ionization (dashed line) and direct pair production (dotted line). Image with courtesy of dr. Dieter Heck 25
4.1 The interaction height of the primary particles simulated with the dpmjet module as a function of the cosine zenith angle (black). Also shown are distributions for showers with a muons laterally separated more (blue) and less (red) than 135 m. 32
4.2 The distribution of the true energy as a function of the cosine zenith angle as simulated with CORSIKA, using the SIBYLL module for high energies, for muons with the largest separation from the shower core, passing all the quality cuts. Also shown are fits to the minimum and average energy.  
4.3 The scaled differential event distribution as a function of the cosine zenith angle for different particle interactions, with 0 being horizontal and 1 being vertical showers. The curves have been scaled to the peak bin and the mean energy of the muons is 2 TeV (±10%).  
4.4 The number of events per bin as a function of the LS muon separation after applying al selection criteria for both data and simulation. The off time data shows the differential rate of randomly coinciding showers that passed all cuts.  
4.5 The corrected data, as it would have been observed at the surface of the Earth, as a function of the LS muon separation. The solid black line shows the full fit of equation (4.3). The red dotted line shows the exponential part of the fit and the blue dashed line shows the power law part of the fit.  
4.6 The number of events per bin as a function of the cosine zenith angle after applying al selection criteria for both data and simulation. The off time data shows the differential rate of randomly coinciding showers that passed all cuts.  
4.7 The ratio of simulation results to data as a function of the cosine zenith angle of the shower bundle after applying all selection criteria.  
4.8 The minimum and average LS muons transverse momentum as a function of cosine zenith angle for all LS muons that pass all the selection criteria, using equation (4.3) and the interaction height from figure 4.1.  
5.1 The CR showers simulated with CORSIKA can save the partial history of a particle. The information known of primary particle, the muon, its parent and grandparent are the 3D location and direction at the end of their tracks, which for the muon is at the observation level. Interaction that take place before between the primary interaction and the end of the grand parent’s life are not known, but are in general not necessary. Note that a muon can have anywhere between one and many parents, but only the last two parents are registered.  
5.2 The prompt flux as generated by CORSIKA simulations, using DPMJET (blue) and QGSJET (red) as interaction model. The black solid line shows the prompt flux predicted by Thunman et al.  
5.3 The non-prompt, or conventional, flux as generated by CORSIKA simulations, using DPMJET (blue) and QGSJET (red) as interaction model. The black solid line shows the non-prompt flux predicted by Thunman et al. The contributions of pions (dotted lines) and kaons (dashed lines) are separately shown as well.  
5.4 The ratio between the CORSIKA interaction models DPMJET and QGSJET of the simulated muon flux fraction from pions (blue) and kaons (red).
5.5 The minimum energy a muon requires to reach the top of the detector under the ice as a function of the cosine zenith angle. The solid line shows the minimum energy for all muons and the dotted line shows the minimum energy for the lateral separated muon.

5.6 The differential muon rate at the observation level as simulated by CORSIKA using the DPMJET interaction module. The different lines represent the various parents, i.e., charmed mesons (red), kaons (green) and pions (blue), that created the observed muons. The black solid line shows the overall spectrum.

5.7 The differential lateral separated (LS) muon flux as a function of the separation distance (black open symbols). The fractional contributions to the LS muon flux from the different parents are shown as well, for pions (blue), kaons (green) and charmed mesons (red). All muons are above the zenith angle dependent minimum energy required to reach the top of the detector under the ice (see figure 5.5).

5.8 The differential muon flux as a function of the cosine zenith angle. The black solid line shows the overall flux, whereas the other solid lines show the fractional muon flux for different parents, i.e., pions (blue), kaons (green) and charmed mesons (red).

5.9 The fractions of the muon flux made up by various parents, as simulated by CORSIKA with the interactions models DPMJET (closed shapes) and QGSJET (open shapes), as a function of the cosine zenith angle.

5.10 The differential muon flux as a function of the transverse momentum, as simulated by CORSIKA using the DPMJET interaction module. The black solid line shows the overall flux, whereas the other solid lines show the fractional muon flux for different parents, i.e., pions (blue), kaons (green) and charmed mesons (red).

5.11 The fraction of the muon flux resulting from either pions (blue), kaons (green) or charm mesons (red) as a function of the transverse momentum, as simulated by CORSIKA using the DPMJET interaction module.

5.12 The transverse momentum of the lateral separated muon, $p_T$, as a function of the lateral separation, $d_T$. All muons are above the zenith angle dependent minimum energy required to reach the top of the detector under the ice (see figure 5.5). The black open symbols show the relation for all muons in a simulated shower, whereas the blue closed symbols show the relation for only the LS muon in each simulated shower.
6.1 A schematic representation of the simulation approach: Standard down-going simulations are created and subsequently extrapolated to the other side of the Earth. Here $\theta$ is the zenith angle, i.e., the angle between the track and the surface normal, $\psi$ the openings angle between the neutrinos, $D$ the perpendicular distance between the two neutrinos after extrapolating their paths, $R_{\text{obs}}$ and $R_{\text{atm}}$ the distance from the Earth’s core to the observation level and the edge of the atmosphere respectively and $L$ the extrapolated path length through the Earth. 

6.2 Plotted is the 2D field where the openings angle $\psi$ is allowed according to equation (6.3) and (6.4). The vertical axis describes the perpendicular distance between two particles at the observation level, i.e., the height at which the simulation writes out the particle data. The horizontal axis is in cosine zenith angle, with 0 being horizontal and 1 being vertical incoming neutrino pairs.

6.3 The probability of detecting a pair of particles in a detector of size $R_{\text{max}} = 1000$ m, given the detection of one of the particles and their separation, as a function of the perpendicular separation between the particles at the detector.

6.4 The primary energy spectrum generated by CORSIKA. The horizontal axis shows the logarithmic energy of the primary particle and the vertical axis shows the number of simulated events falling in each bin. The spectral index of the simulations is $dN/dE_p \propto E_p^{-1}$. The total number of simulations is 100,000.

6.5 The primary zenith angle spectrum generated by CORSIKA. The horizontal axis shows the normal component of the zenith angle, i.e., $\cos \theta$, of the primary particle and the vertical axis shows the number of simulated events falling in each bin. The total number of simulations is 100,000.

6.6 The probability of detecting one neutrino pair originating from a single cosmic ray shower as a function of the primary energy.

6.7 The differential event rate as detected by IceCube as a function of the primary energy.

6.8 The differential event rate as detected by IceCube as a function of cosine zenith, i.e., the normal component of the zenith angle.

6.9 The predicted event rate in a detector with a diameter of $D_{\text{max}}$. 

71
## List of Tables

3.1 Most common Kaon decay modes and their respective branching ratios 28

3.2 Most common Charm decay modes and their respective branching ratios 29

5.1 The fitted parameters of equation (4.3) to the simulated data from DPMJET compared to the data from the Lateral Separated muon analysis. 46

6.1 The fitted parameters of equation (6.14) for both interaction models, i.e., QGSJET and DPMJET, and for both types of primary particles, i.e., Protons and Iron. 60

6.2 The predicted event rates in IceCube depending on the used interaction model and the used primary particle. 61
References


[21] “High resolution fly’s eye website.” 1

[22] Studies of Cosmic Ray Composition and Air Shower Structure with the Pierre Auger Observatory. 31st International Cosmic Ray Conference, July 2009. 1


[25] D. Heck, Charm in extensive air shower simulations with corsika. 9, 29, 73, 27


75
REFERENCES


