# The Role of Pions in Air Shower Simulations

Lotta van Broekhoven
Supervisor: Harm Schoorlemmer

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## Abstract

The number of muons measured in experiments does not coincide with the number of muons that is predicted by the hadronic interaction models. There is a muon deficit the hadronic interaction models. This article focuses on the pions which are created in these simulations. The influence of the initial energy on the percentage of energy going into the neutral pions has been investigated. A higher initial energy leads to a higher percentage of energy going into the neutral pions. The charged pions and their decay into muons have also been investigated. These calculations lead to maximally 15% more muons. Next the treatment of pions in three different hadronic interaction models is discussed. Here, differences between creation of charged and neutral pions were found.

## 1 Introduction

In outer space there are many high energetic particles. These high energetic particles, which are mainly protons, but can also be atomic nuclei, are called cosmic rays. These cosmic rays can eventually reach the earths atmosphere. In the earths atmosphere the density is far higher than in outer space, leading to interactions with the cosmic ray. Processes like this happen many times a day depending on the energy of the cosmic ray [1]. This interaction of the cosmic ray leads to the creation of many new particles, which will cause a cascade effect of particle creation. Such a cascade of newly created particles is than called an air shower. Eventually some of these created particles will make it to the surface of the earth. Here the incoming particles can be detected. Next to the detection of the air showers it is also possible to make simulations of the air showers. These simulations can be used to study the air showers in more detail. However, these simulations are not a perfect representation of the actual measurements of the air showers. There are still some differences between the simulations and the measurements. A prominent difference is the number of muons that is predicted by the simulations and what is being measured by the experiments. Namely, there is a muon deficit in the hadronic interaction models which are used for the simulations [2]. In this article there will be looked at the behaviour of the pions in air showers simulations, since the decay of charged pions will lead to the creation of muons. For these simulations three different interaction models will be used to compare the pion behaviour. This might lead to a better insight in the working of air showers and the different interaction models.

## 2 Air showers

When a high energy cosmic ray reaches the earth's atmosphere, it will interact with a nucleus of an atom in the atmosphere, since the density of the atmosphere is much higher than the density of the interstellar medium. Due to the high energies of the incoming particles, the interaction with the nuclei in the atmosphere results in the creation new particles, which too will have high energies. These newly created particles will travel through the atmosphere and interact again. This process of interaction and creation continues, resulting in a cascade of interactions and the creation new particles, an air shower. However, with each interaction, the energy of the incoming particles gets divided over the created particles. This means that the cascade of interaction and creation ends when the energy of the new particles is not high enough anymore to create new particles. These air showers can be described by the Heitler-Matthews model for extensive air showers [3].

Particles that are numerously created in these air showers are pions. There are three types of pions, the $\pi^+$ , $\pi^-$ and $\pi^0$ . Both the $\pi^+$ and $\pi^-$ are charged pions, while the $\pi^0$ is neutral. This is due to their composition. The pions are mesons and thus contain two quarks, a quark and an anti-quark. The contents of the $\pi^+$ , $\pi^-$ , $\pi^0$ are respectively $(u\bar{d})$, $(\bar{u}d)$ and $(\frac{u\bar{u}-d\bar{d}}{\sqrt{2}})$ [4]. The composition of the pions also explains why the pions are numerously created in the air showers. The up and down quarks are the lightest quarks, making the pions the lightest mesons, allowing them to be created more numerously.

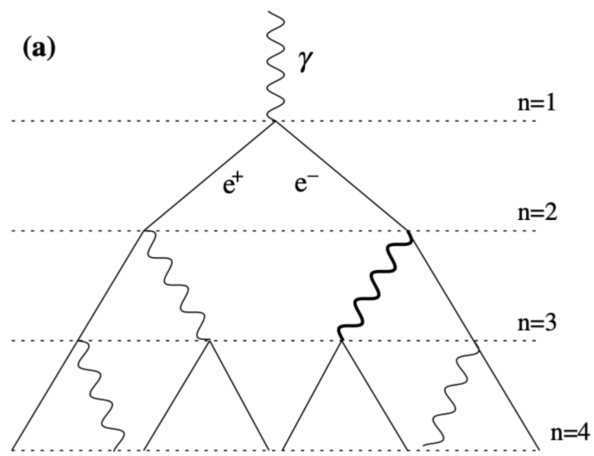



*Figure 1: In this figure a schematic version of an electromagnetic airshower is shown. The incoming photon is a decay product of a $\pi^0$ . The photon creates an electron-positron pair an level n=1. Both the electron and positron send out photons as bremsstrahlung at level n=2. These photons also create electron-positron pairs, leading to more bremsstrahlung being emitted. Which will again lead to more electron-positron pairs. This process stops if the energy is not sufficient anymore. [3]*

## 2.1 Electromagnetic air showers

The neutral pions, $\pi^0$ , have a lifetime of $\tau = (8.43 \pm 0.13) \times 10^{-17} s$ [4]. As a result of this very short lifetime, $\pi^0$ travel through the atmosphere very shortly. Because of this extremely short lifetime, they almost instantly decay, without interacting with nuclei in the atmosphere. The $\pi^0$ will decay into two photons, $\pi^0 \rightarrow \gamma\gamma$.

The photons created in this process will then each decay into an electron-positron pair, $\gamma \rightarrow e^- e^+$. The electron and positron will in turn each send out photons in the form of bremsstrahlung. These photons will again decay into an electron-positron pair. Via this mechanism the process of creating photons and electron-positron pairs will continue if the energy of the particles is sufficient. Thus, the result of the creation of a $\pi^0$ is a cascade of photons, electrons and positrons. With every step in the cascade more electromagnetic particles get created, until the energy of the particles is not sufficient anymore to allow the cascade to go on. This means that the creation of a $\pi^0$ leads to an electromagnetic shower. A schematic version of an electromagnetic air shower is shown in figure 1.

### 2.2 Hadronic air showers

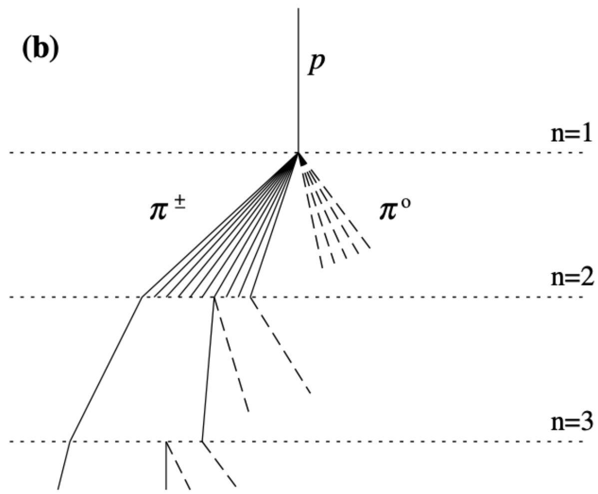



*Figure 2: This figure shows a schematic version of a hadronic air shower. The incoming particle is a proton, which interacts and leads to the creation of $\pi^0$ , $\pi^+$ and $\pi^-$ , as can be seen in level n=1. The $\pi^0$ will go and create electromagnetic air showers. The $\pi^+$ and $\pi^-$ can again create both charged and neutral pions, resulting in a hadronic air shower. [3]*

Next to the neutral pions, there are also positively and negatively charged pions, $\pi^+$ and $\pi^-$ . The charge of the pions is not the only difference between the $\pi^0$ and $\pi^{\pm}$, their decay times are also very different. The $\pi^+$ and $\pi^-$ have decay times of $\tau = (2.6033 \pm 0.0005) \times 10^{-8} s$ [4]. The decay products of a $\pi^+$ and $\pi^-$ are also different, $\pi^+ \rightarrow \mu^+ + \nu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}$.

This longer lifetime allows the $\pi^{\pm}$ with high enough energies to interact with the nuclei in the atmosphere instead of decaying. These interactions allow for more particles to be created, among which both neutral and charged pions. The neutral pions will continue to create electromagnetic showers as described above. The created $\pi^+$ and $\pi^-$ can again lead to an interaction with a nucleus, creating new particles and repeating the process. This results in a hadronic air shower. When the energy of the $\pi^+$ or $\pi^-$ is not sufficient enough to create new particles, the $\pi^+$ or $\pi^-$ will decay into the muons and neutrinos, causing cascade to end. A schematic version of a hadronic air shower can be seen in figure 2.

This means that a hadronic shower can lead to both more $\pi^{\pm}$ and to electromagnetic showers. However, all the energy that goes into the creation of $\pi^0$ ends up in the electromagnetic showers and cannot be used to create $\pi^{\pm}$ again.

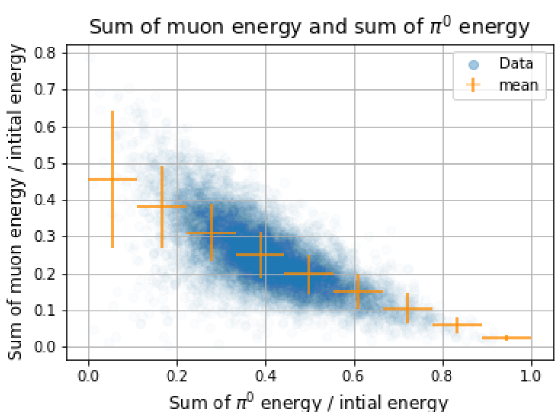
# 3 Air shower simulations

In order to get a better understanding of the working of air showers and the role of the pions in the air showers various air showers were simulated using CORSIKA [5], version 7.7410. The hadronic interaction models used for these simulations are EPOS-LHC [6], QGSJET-II-04 [7] and SIBYLL 2.3d [8]. CORSIKA provides the results of the air showers at the ground level. However, it does not provide all the processes that occur during the air shower. In order to get information from the air shower as it is being formed, COAST [9] was run together with CORSIKA. Using COAST all the necessary information of the wanted particles can be analysed. This is extremely useful to be able to get a complete picture of all the wanted aspects of an air shower.

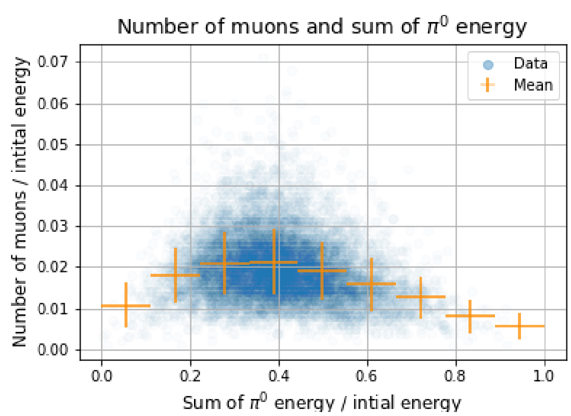
Sets of air shower simulations were made for different energies of the initial particle, while the other parameters of the simulations were kept the same between the different sets of simulations. Each of the sets contained 10000 air shower simulations. The initial energies of the sets were fixed at 1 TeV, 5 TeV, 10 TeV, 50 TeV and 100 TeV. These energies were chosen because they cover a wide energy range and fall well within the preferred energy ranges for the different hadronic interaction models.

For all simulations the primary particle, the target and their interaction height were kept the same. The primary particle was set as a proton, the target as nitrogen. The first interaction height was fixed at 25 kilometers. Around the height of 25 kilometers the atmosphere starts to become much more dense, hence why 25 kilometer is a feasible height for the first interaction. The ground level of theses simulations was set at 0 kilometers. The zenith angle is set to 0 degrees resulting in ~~mainly~~ vertical air showers.

# 4 Neutral pions




*(a) Relation muon energy*




*(b) Relation number of muons*

*Figure 3: The relation between the sum op neutral pion energy of the air showers with the sum of the muon energy and the number of muons created in the air showers respectively. The orange lines show the mean of the data. The data points themselves have been made ~~more~~ transparent. The initial energy of the air showers was 1 TeV, and the models was EPOS.*

As explained above, the neutral pions play a big role in dictating where the energy goes in the creation of air showers. All the energy of a neutral pion will end up the electromagnetic showers. Because of this, it is important to have a look at the percentage of the initial energy that will go into the creation of neutral pions.

As described in section 2.2 there is a clear relation between the energy of neutral pions and the energy of the muons. Energy going into neutral pions cannot end up going into muons anymore. This is a result of the electromagnetic air shower that is formed when a neutral pion decays. All the energy of the neutral pion is being put into electromagnetic particles. As a result of this, there is ~~perceptually~~ less energy available to go into the creation of muons. From this, it can be derived that a higher percentage of $\pi^0$ energy of an air shower would results in a lower percentage of muon energy. This relation between the energy that can go into the neutral pions and the energy that is available to go into the muons can be seen in figure 3a.

In figure 3a the relation between the energy of the muons and the energy of the pions can be seen, here the 1 TeV air shower is taken as the example. This figure indeed shows the relation as described above. On the left side of the figure, there is a lower percentage of energy going into the creation of neutral pions. This allows for more energy to go into the creation om muons. As the energy percentage of the neutral pions increases, the available energy for the muons decreases.

Another sanity check for this figure is to make sure there are no data points for which the percentage of muon energy and the percentage of $\pi^0$ energy combined is bigger than 1. This should not be the case, since that would result in more available energy than the initial energy of the air shower.

Next to looking at the relation between the energy going into the muons and the energy going into the neutral pions, the relation between the energy going into the neutral pions and the number of muons can be discussed. The figure showing this relation is figure 3b.

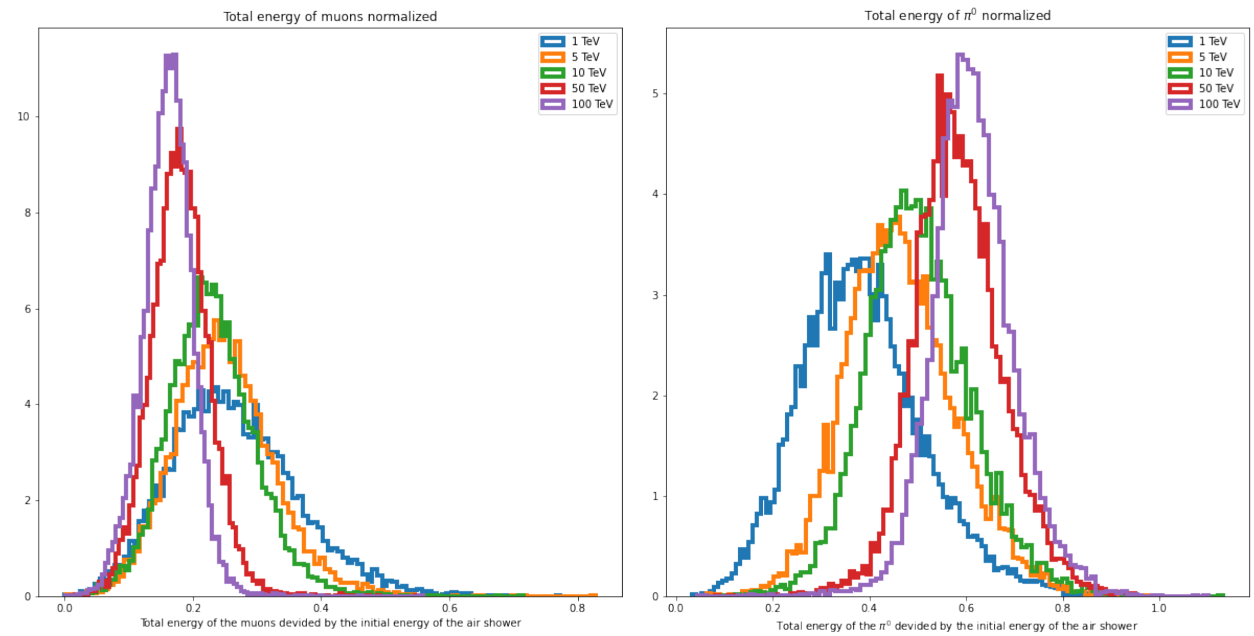
In figure 3b it can be seen that the relation between the $\pi^0$ energy and the number of muons created in the air showers is much less prominent. For higher percentages of $\pi^0$ energy, here around 30 percent, it can be seen that the increase of $\pi^0$ energy does lead to a smaller amount of muons that are created. However, the relation is very weak. As for lower $\pi^0$ energy percentages, the number of muons even gets smaller. In this area, there are most likely air showers created which contained fewer pions in general. Thus not putting a lot of energy in the $\pi^\pm$ and not putting much energy into the $\pi^0$ . Thus figure 3b shows more of a central cluster than a clear relation between the energy going into the $\pi^0$ and the number of muons.

Now it is also possible to compare figure 3a and 3b. They share the same values on the x-axis and both have properties of the muons on their y-axis. But despite these similarities they do also show differences. Figure 3a shows a clear relation between the percentage of $\pi^0$ energy and the muon energy. This clear relation cannot as clearly be found in figure 3b, since it shows more of a central cluster than a clear relation.

So far, there is looked at the percentage of the air shower energy that went into the neutral pions and comparing this to the percentage of energy that went into the muons or the number of muons created in the air showers. Next to this comparison it is also possible to look at the percentage of the energy of the air showers that went into the creation of neutral pions in the form of histograms. In other words, the values of the x-axis of the figures 3a and 3b represented by histograms.

The histograms of the total energy that went into the muons and neutral pions in the air shower simulations are shown in figure 4. The total energy of the muons and neutral pions is divided by the initial energy of the air shower. This allows for a more clear comparison. The mean of the histograms thus represents the percentage of the total energy that went into the creation of muons or neutral pions, where a value of 1 corresponds to all the energy and

0 to no energy.




*(a) Muon distribution*

*(b) Neutral pion distribution*

*Figure 4: The distributions of muons and neutral pions for air showers with different initial energies. The energy that went into the muons and neutral pions is divided by the initial energy of the air shower.*

As can be seen in figure 4a, the percentage of energy that goes into the muons decreases as the initial energy of the air showers increases. The opposite relation can be seen in figure 4b. Here the percentage of the energy that goes into the neutral pions is shown. As the initial energy increases, the percentage of neutral pion energy also increases.

The means values of these histograms can also be represented in a single graph, figure 5. The error on the means are derived from the standard deviation of the histograms and the number of air showers. As the initial energy of the air showers increases the percentage of the energy going into the neutral pions increases, while the percentage of the energy going into the muons decreases. The reason why the energy going into the muons decreases as the energy going into neutral pions increases can be explained by looking back at section 2.2. As the percentage of the energy going into the neutral pions increase, the percentage of energy left for the creation of charged pions that can decay into muons starts to decrease.

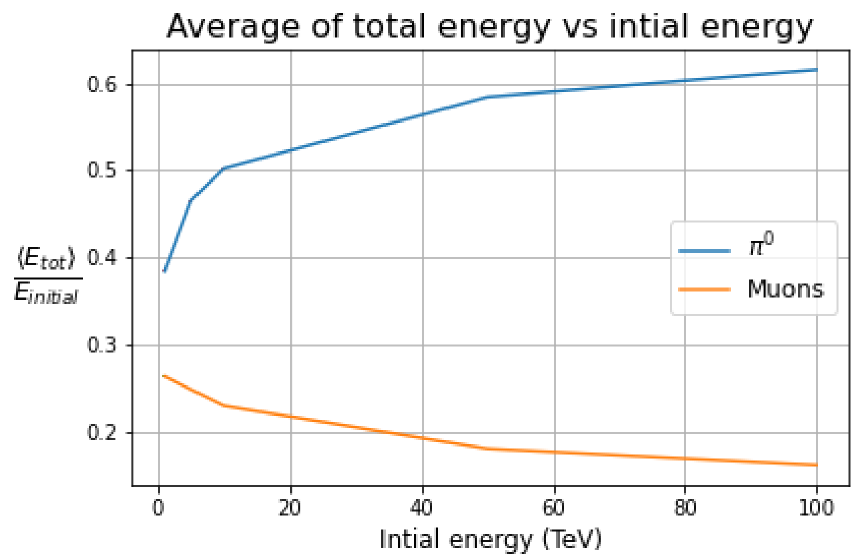



*Figure 5: The ~~percentage~~ of the energy of the air showers that went into the neutral pions and the muons with respect to the initial energy of the air showers. The error on the percentages are shown, however they are very small.*

# 5 Effects of the Atmosphere on air shower development

## 5.1 Pion interaction length

Next to looking at the neutral pions in the air shower simulations, it is also insightful to have a look into the charged pions. These are the particles that can eventually lead to the creation of the muons in the air showers. However, not all pions will lead to the creation of muons. As discussed in section 2.2, the charged pions can also interact with other particles before they get the chance to decay into muons. Here, the most important factors that decide whether the charged pion will decay or not are discussed.

A factor that is of great significance for the formation of the air showers is the earths atmosphere. As discussed in section 2.2, a $\pi^{\pm}$ can decay into muons, but only if they do not interact with other particles first. When the $\pi^{\pm}$ encounter more nuclei in the atmosphere, the probability for the pions to interact with these nuclei gets higher. This means that the probability for the pions to interact or decay is thus dependent on the distance that the pions travel through the atmosphere and the density of the atmosphere itself. The relation between the density of the atmosphere and the altitude can be seen in figure 6.

As can be seen in figure 6, the atmosphere is far less dense for higher altitudes than it is for lower altitudes. As a result of this, the pions that are created higher in the atmosphere encounter less nuclei from the atmosphere compared to the pions that are created in lower regions of the atmosphere. Therefore, a $\pi^{\pm}$ that is created at higher altitude is more likely to decay into a muon than a $\pi^{\pm}$ with the same energy at a lower altitude.

However, the number of nuclei encountered in the atmosphere by the $\pi^{\pm}$ is not solely dependent on the altitude at which the pions are created. The energy of the created pions also plays a role in this process.
When a pion has a higher energy, it is able to travel further than a pion with less energy. Consequently, the pion with

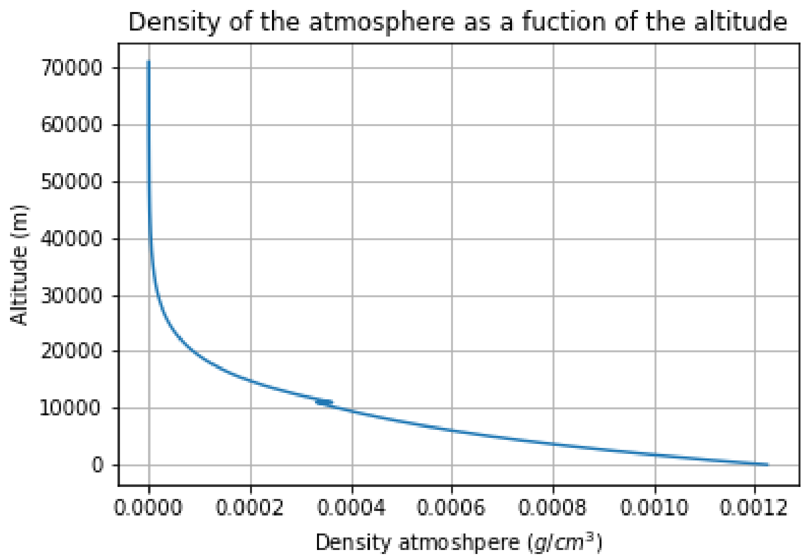



*Figure 6: This figure shows the density of the atmosphere for different altitudes.*

a higher energy will go through more atmosphere, resulting in a higher probability of interacting with a nucleus in the atmosphere. This can be expressed by the slant depth, as described by equation 1. Here the $\rho$ is the density of the atmosphere at height $h$. For these calculations the US Standard Atmosphere was used [10].

$$X = \int_{\text{initial height}}^{\text{finial height}} \rho(h)\,dh \tag{1}$$

The interaction length of a pion in the earths atmosphere is $\lambda \approx 120$ g cm$^{-2}$ [11]. This means that a $\pi^{\pm}$ that travels through the atmosphere will interact with a nucleus in the atmosphere if the pion encounters more than 120 g cm$^{-2}$. If the $\pi^{\pm}$ encounters less than than 120 g cm$^{-2}$ as it travels through the atmosphere it will decay.

Figure 7 shows the regions where the pions can decay for different creation heights and energies. Pions which are created in the green area have a possibility to decay, the pions created in the red area will interact with a nucleus in the atmosphere, and do not decay. As can be seen in the figure, pions with a lower energy can decay at much lower altitudes than the pions with a higher energy. The pions with the lower energy will move slower through the atmosphere, and thus will not travel as far as the pions with a higher energy. Because of the shorter travel distance, they encounter less of the atmosphere, making the possibility to interact with a nucleus in the atmosphere smaller. The travel distance is less important at higher altitudes, since the atmosphere is much less dense at higher altitudes, as could be seen in figure 6. Because of this, it is still possible for pions with very high energies to decay, but only if the altitude at which these pions are created is high enough, allowing the pions to travel through the atmosphere without encountering any nuclei.

With the help of figure 7 the initial energy dependency of figure 5 can be explained. For the lower energetic air showers, so the air showers with lower initial energies, the pions will also have mainly low energies. Due to these lower pion energies the pions they have higher probabilities to decay into muons. This can be seen in figure 7. As the energy of the pions increase, the possibility for them to decay gets smaller. As the charged pions interact

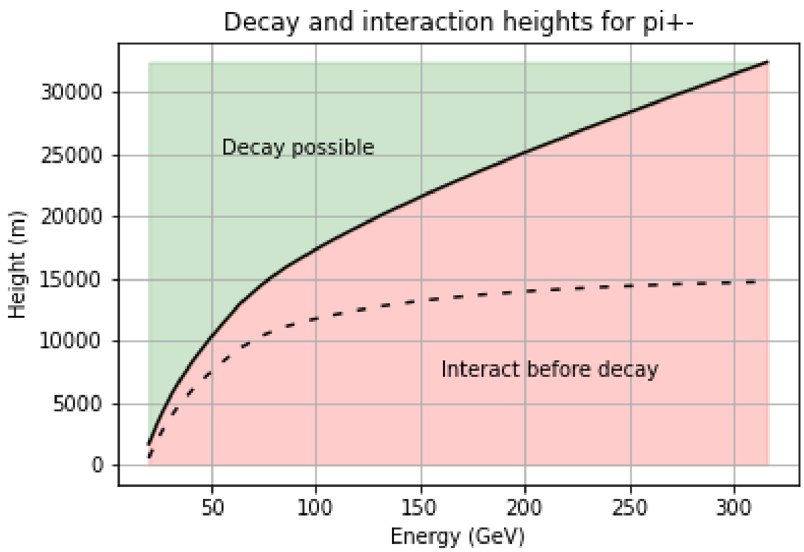



*Figure 7: This figure shows the regions where the created pions can decay or interact. The green area represents the region where the created pions can decay into muons. If a pion is created in the red area, it will encounter too much atmosphere in order to be able to decay. This means that the pions created in the red area will interact with the nuclei in the atmosphere. It is possible for a pion that is created in the green area to travel to the red region and decay there. The dashed line shows the height at which the pions that are created on the border between the two areas will decay.*

again, they can also create neutral pions in the process. And once the energy is being put into the neutral pion, it cannot be used anymore to create other muons, because the neutral pions will lead to an electromagnetic shower. So as the initial energy of the air showers increases the energy of the pions also increases. But if the energy of the charged pions is too high, they interact before they get the chance to decay, allowing for more neutral pions to be created. Hence why the percentage of the energy into the neutral pions increases and the percentage of energy into the muons decreases as the initial energy gets increased, just as it is shown in figure 5. Next to the higher chance of decay for higher energetic $\pi^{\pm}$ the lower energies of the muons also play a part in the behaviour of figure 5. If the energies of the muons are lower, the percentage of the energy of the muons will be higher if the initial energy to which it is being compared is lower as well.

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## 5.2 Muon energy loss due to the atmosphere

The charged pions are not the only particles important in the process for the creation of muons that are effected by the earths atmosphere. The muons themselves are also effected by the density of the atmosphere. The way the atmosphere effects the muons is by causing the muons to lose some energy as they travel through it. A muon loses about 2 MeV per g cm$^{-2}$ of the atmosphere [12]. This means that if a muon travels through 1000 g cm$^{-2}$, which is roughly the whole atmosphere, it would lose 2 GeV.

The effects of the energy loss on the muons is shown in figure 8. Here, the effects of the energy loss of the muons can clearly be seen. At lower altitude, the effect is minimal. However, when the muons are created at higher altitudes, the percentage of muons reaching the ground start to differ more. For the muon energy of 1.5 TeV the maximum difference around 38% around 9 kilometers. This shows the importance of incorporating the energy loss of the muons.

GeV???

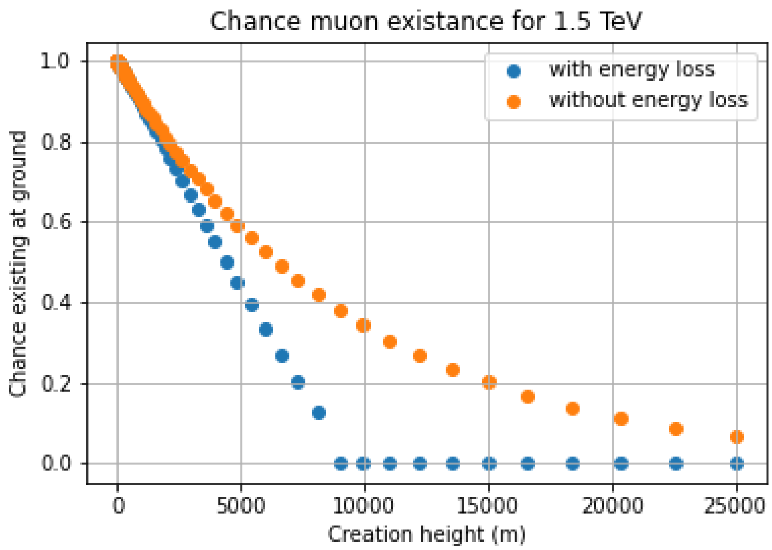



*Figure 8: Chance of the muon reaching the ground for different creation heights. The blue line shows the model with an energy loss of 2 MeV per g cm$^{-2}$, while the orange line does not include the energy loss of the muons. The energy of all the muons is 1.5 TeV.*

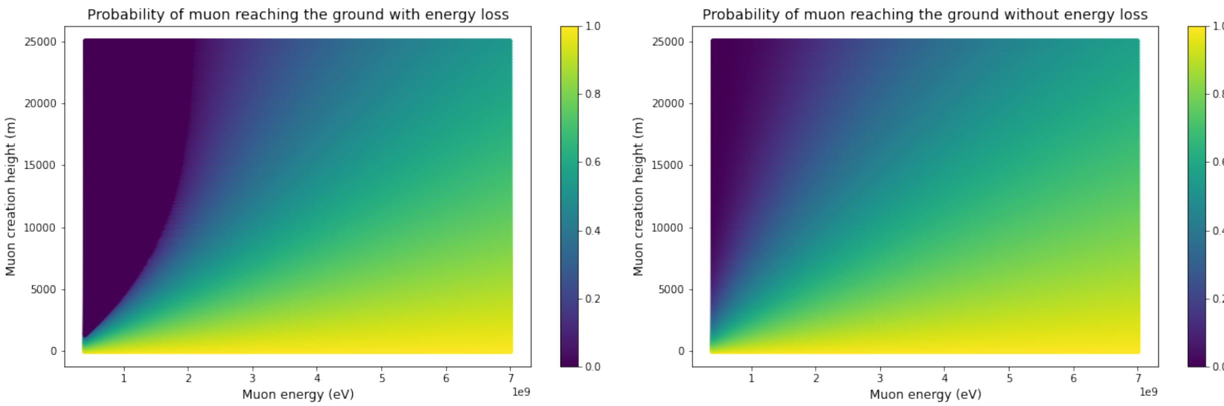
GeV???

The way the energy loss of the muons was determined is by dividing the atmosphere up in different slices. Using the begin and end height of these slices the slant depth of these slices can be calculated. From this, the energy loss of the muons traveling from one slice to another can be calculated by taking the energy loss to be 2 MeV per g cm$^{-2}$. Now the energy loss of all the slices of the atmosphere can be determined. The energy of a muon at every slice of the atmosphere can now be determined by setting the initial energy and height of the muon. The chance that a particle decays is dependent on the energy of the particle. This can be seen in equation 2.

$$P_{existing} = exp\left(\frac{-t}{\gamma * \tau}\right) \tag{2}$$

Here, $t$ represents the time that it takes the muon to travel through a slice of the atmosphere with the energy belonging to this slice. The gamma factor is also a function of the energy of the muon. The $\tau$ is the mean lifetime of the particle, $\tau$ = (2.1969811±0.0000022 ) $10^{-6}$ s [4]. Thus the chance of the particle existing is dependent on the energy of the particle. By using the calculated energy of the muon at a slice of the atmosphere it is possible to get the chance that the muon exists at all the different slices. When all these chances of a single muon traveling through the atmosphere get multiplied, total chance of that muon reaching the ground can be determined. By calculating this chance for muons of various heights at various energies figure 9 can be made.

Figure 9a shows the probability of a muon reaching the ground for different energies and at different creation heights when taking the energy loss into account. The yellow area shows where the muons have a high chance of reaching the ground. The purple area shows the region with a low chance.




*(a) With energy loss* *(b) Without energy loss*

*Figure 9: The probability of a muon reaching the ground. The energy of the muon is plotted against the height at which the muon is created. The yellow area shows where the muons have a high chance of reaching the ground. The purple area shows the region with a low chance.*

Figure 9b shows the probability of the muons reaching the ground without the energy loss of the muons. Especially the region for lower energetic muons, so below around 3 GeV, is different compared to the probability when energy loss is taken into account. Because the initial energy of the muons in this region is already quite low, the energy loss will have a bigger effect on the total energy of the muons. So in other words, the muons with less energy lose ~~perceptually~~ more energy. For low energetic muons that are created at very low altitude this effect is less prominent. Because of their low creation height, they will not travel though the atmosphere very far. And since the energy loss is dependent on how much g $cm^{-2}$ of the atmosphere the muons encounter, the energy loss will not be very high for muons that do not travel through the atmosphere very far, even though the atmosphere is most dense at lower altitude.

On the right side of the figures, i.e. the region with the higher energetic muons, the graphs appear to be quite similar. And at the lower altitudes, this is indeed the case. Here, the effects of the energy loss are extremely small. As explained before, the muons simply do not travel through a lot of atmosphere when they are created at lower altitude, resulting in a very low contribution of the energy loss.
At higher altitudes, the difference between the probability of the muons reaching the ground with and without energy loss taken into account is around 5 percent. This difference is much lower that the difference at higher altitudes for lower muon energies. For higher energetic muons, the energy loss compared to their initial energy is much lower. So for higher energetic muons, they lose percentually less energy. However, even though the effects of the energy loss are much smaller, there is still a difference between the probabilities of the muons reaching the ground with and without energy loss.

# 6 Number of muons at the ground

Now the behaviour of the pions and the effects of the energy loss have been described, it is possible to have a look at the number of muons that reach the ground. From the simulations the energy and the initial height of the $\pi^{\pm}$ can be extracted. The distance that a $\pi^{\pm}$ travels through the atmosphere can be calculated. Using this information, the slant depth of the charge pions can be determined. When the slant depth exceeds 120 g cm$^{-2}$, the pion will not decay, because it exceeds the interaction length of the charged pion. However, when the slant depth is less than 120 g cm$^{-2}$, the pion gets the chance to decay. This final height of the charged pion is than used as the creation height of a muon. By using figure 9 the chance of the muon reaching the ground can be determined, since the creation height and the energy of the muon are known. This results in a chance of the muon reaching the ground. This chance is then compared to a random number between 0 and 1. When the chance of the muon reaching the ground is bigger than the random number, the muon will be counted as reaching the ground. When the random number is bigger, the muon will not have made it to the ground. By using this method the number of muons can be counted with the information of the height and energy of the charged pions. The code for this method is available at ~~GitLab~~. When using this method for counting the number of muons some assumptions have been made:

- Only charged pions decay into muons.
- The muons travel straight down towards the earth. The trajectory of the muons is perpendicular with respect to the surface of the earth.
- The energy loss of the muons is always 2 MeV per g cm$^{-2}$ of the atmosphere.

Figure 10 shows the results.

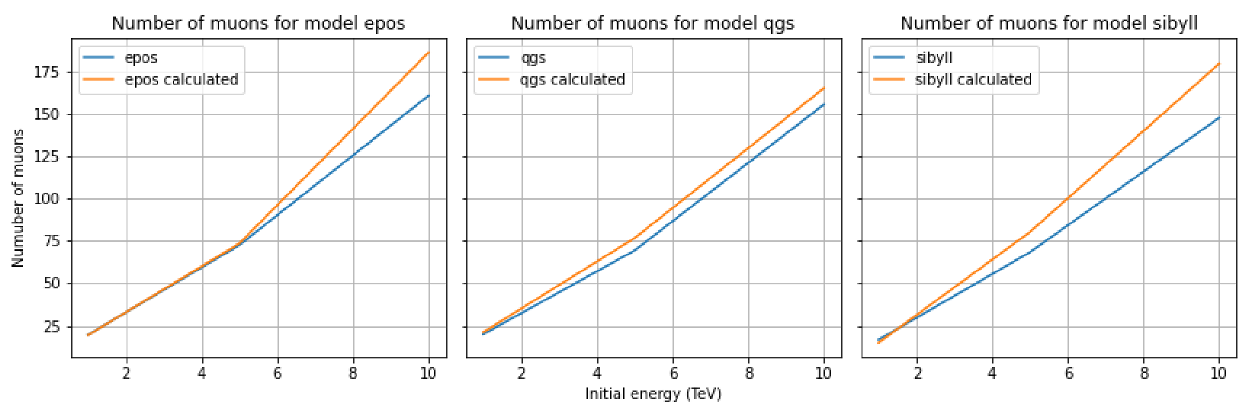



*Figure 10: The number of muons for the different muons, both calculated with the described model and the number that follows from the simulations.*

Figure 10 shows the number of muons that were calculated using the above described method as well as the results according to the simulations for the different models at different initial energies. As can be seen in the figure, the calculated number of muons is slightly higher than the number of muons according to the simulations. The difference between the number of muons from the simulations and the calculated number is around 15% for both the EPOS and SIBYLL model at 10 TeV. The QGS model differs by about 6% at the same energy.

To get a better understanding of the difference in the number of muons, it can be insightful to look at the energy distribution of the muons reaching the ground. This distribution can be seen in figure 11. Because the number of muons differs for the different approaches the density is used in the figure.

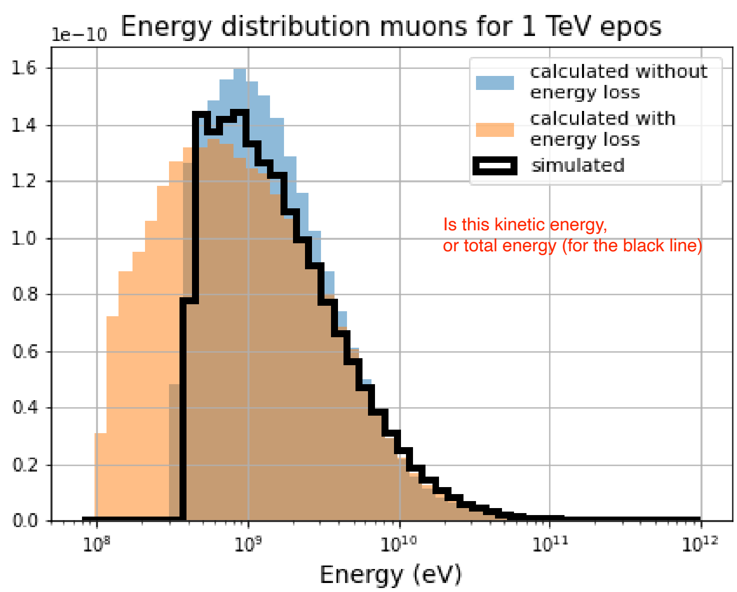



*Figure 11: The energy distribution of the muons reaching the ground. The black line shows the distribution of the muons from the simulations. The blue histogram shows the distribution if there were no energy loss in the muons. The orange histogram is the distribution with the energy loss taken into account. The values on the x-axis is logarithmic, just like the bins sizes. The number of muons is taken out by using the density.*

As can be seen in figure 11, the calculated distribution with energy loss contains more low energetic muons. The lowest energetic muons of the simulated data have energies of around 0.4 GeV. However, the minimum of the calculated muon energy with the energy loss is slightly higher than 0.1 GeV. There are also less muons created by the model with energy loss in the energy region of 10 GeV to 100 GeV compared to the simulated distribution.

The distribution for the calculated number of muons without taking energy loss of the muons into account has more muons in the 1 GeV region than the simulated distribution. However, the low energy problem that the calculated distribution with energy loss had is not the case for this distribution.

## 7 Energy distribution of pions and muons

Next to looking at the behaviour of the different pions in the air showers, it is also possible to look at the differences between the hadronic interaction models that are used to create the simulations of the air showers. One way to get an insight into the different models and their differences is by looking at the energy distributions of the different models and comparing them.

Figure 12 shows the differences between the energy distributions of neutral pions created in air showers with an initial energy of 100 TeV. The EPOS model is taken as a baseline to which the energy distributions of the other models are being compared. From this figure it is clear there are some differences between the models in the way they treat the neutral pions. On the left side of the graph the lowest energetic pions are shown, i.e. the pions with energies below 10 GeV. Here both the SIBYLL and the QGS model create less neutral pions than the EPOS model

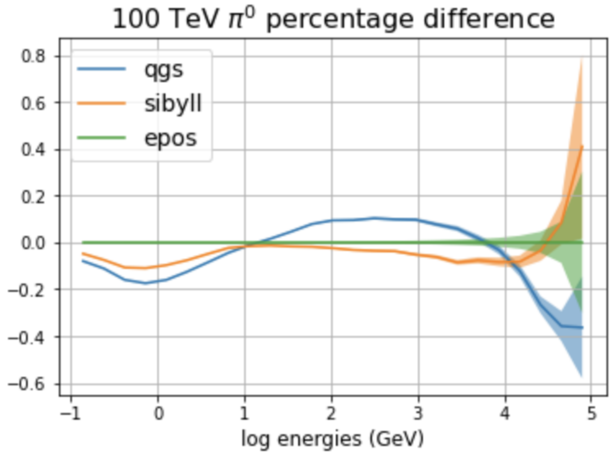



*Figure 12: The energy distribution of the neutral pions for different models. The y-axis shows the percentual differences between the models with the EPOS model as baseline. The values on the y-axis have to be multiplied by 100 to get the actual percentages, so a value of 0.5 corresponds to a difference of 50 percent.*

does for 100 Tev air showers. The EPOS model creates around 20% more low energetic muons than the QGS model and around 10% more than the SIBYLL model does in this energy range.

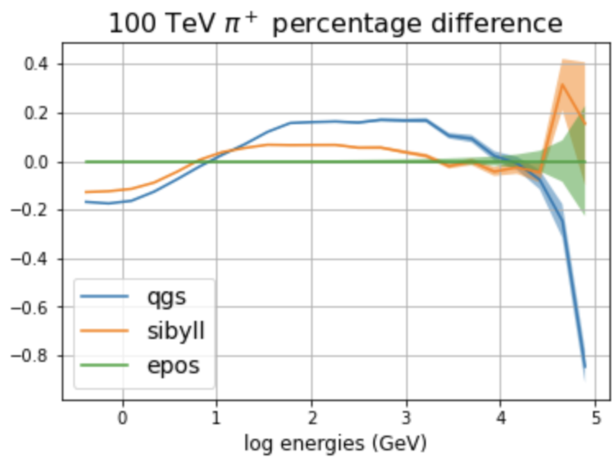
In the energy range of 10 GeV to around 10 TeV the models differ again, but in different ways than they do for the lower energetic neutral pions. In this region the QGS model creates the most neutral pions, about 10% more than the EPOS model does. However the SIBYLL model creates less neutral pions in this energy range. Near the 10 TeV pions this difference tends to 10 percent.

For the highest neutral pions that are created in the air showers, the models each differ quite a lot. The SIBYLL model creats more of these high energetic pions. Whereas the QGS model does the opposite and creates less high energetic neutral pions compared to the EPOS model. However in this energy regime, the errors on the distributions starts to get quite large, allowing for a bigger uncertainty in this energy range.

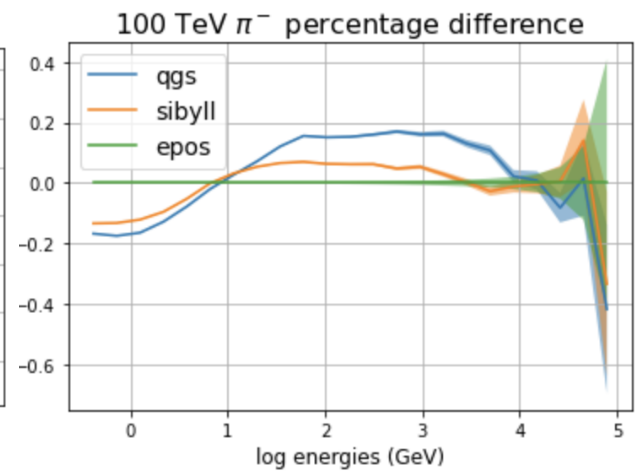
Figure 13 shows the differences between the energy distributions of the different models for the $\pi^+$ and $\pi^-$ . The graphs of the $\pi^+$ and $\pi^-$ show a lot of similarities. They both start with the SIBYLL and QGS model lower than the EPOS model. At around 10 GeV, both the QGS and SIBYLL model will start to create more $\pi^\pm$ in this energy regime than the EPOS model. The QGS model will allow the creation of about 20% more $\pi^\pm$ , while the SIBYLL model will only create around 10% more. Near the end of the energy spectrum of the $\pi^\pm$ the models start to deviate again.

Now it is also possible to compare the charged pions in figure 13a with the neutral pions in figure 12. The QGS model behaves quite similar for all the pion cases. In the energy regime of 10 GeV to 10 TeV the QGS model does create less neutral pions than charged pions. The model creates around 10% more charged pions than the EPOS model, however it creates about 20% more charged pions compared to the EPOS model. In the high pion energy regime, so above 10 TeV, there are also some differences. For all the different pions the QGS makes less high energetic pions than the EPOS model. However, the $\pi^+$ seem to be created less. Although the deviation on the percentual differences is quite large in this pion energy regime.

The SIBYLL model does also show differences between the charged and neutral pions. In the energy regime of




*(a) Positive pions*




*(b) Negative pions*

*Figure 13: These plots show the energy distributions of the $\pi^+$ and $\pi^-$ of the different models. The EPOS model is again taken as a baseline to compare the other models to. The values on the y-axis again have to be multiplied by 100 to get the actual percentages. The initial energy of the air showers is 100 TeV.*

10 GeV to 10 TeV more charged pions get created by the SIBYLL model compared to the EPOS model. However, the SIBYLL model creates less neutral pions in this energy regime.

# 8 Discussion

There is no clear relation between the number of muons and the percentage of the initial energy that went into the creation of neutral pions.

Second, the percentage of the energy that goes into the creation of neutral pions and the creation of muons is dependent on the initial energy of the air showers. This energy dependency is a result of the charged pions interacting with the atmosphere before they can decay. Due to these interactions, more energy can go into the creation of neutral pions. And when the energy went into the creation of neutral pions there is no possibility for it to go into the creation of muons again, because the neutral pions cause electromagnetic air showers.

Third, the energy loss of the muons plays an important role. From figure 8 it can be seen that the energy difference between the muons with and without energy loss can easily be more than 30%. Figure 9 show the different probabilities for the muons reaching the ground with and without energy loss. The difference is most noticeable in the lower energy region. They experience the biggest effect of the energy loss, because the muons in this region have less energy to begin with. So they lose percentually more energy, even though they do not travel as far through the atmosphere as their higher energetic counterparts. However, the energy loss still makes a difference for the higher energies. At higher altitude the muons much further, thus leading to a higher slant depth, which will increase the energy loss. Hence why the effects of the energy loss for higher energetic muons is more prominent at higher energies. Here, the difference between probability of reaching the ground for the muons with and without energy loss is around 5%.

Next, the calculated number of muons does not coincide with the number of muons that were produced in the air shower simulations. The calculated number of muons exceeds the number of muons counted by the simulations. The EPOS and SIBYLL model each have about 15% more muons for the 10 TeV air showers. The QGS model has around 6% more muons for this energy. This could be a result of the assumptions that were made, as described in section 6. As stated in that section, the muons would all travel straight down. However, this is not a very realistic scenario. It is more likely that the muons would travel at an angle towards the earth, instead of arriving perpendicular to the surface. As a result of this angle, the muons would have to travel through a larger section of the atmosphere. This leads to more energy loss and thus smaller probabilities for the muons to reach the earth. The distance towards the surface of the earth would also increase, leading to even less muons. Another assumption that was made in this model was that the energy loss was always 2 MeV per g $cm^{-2}$. However, the energy loss is dependent on the energy of the particle. The relation between the energy loss of the particles and the energy that they have is described by the Bethe-Bloch formula [12].

In the same section, section 6, the energy distributions of the muons at the ground for different approaches is shown. However, the energy distributions differ. The distribution of the muons with energy loss shows too much low energetic muons. In the simulations, these low energetic muons do not reach the ground. This could again be due to the assumptions made in the calculation of the number of muons. The lower energetic muons might not be able to reach the earth if they have to travel a longer distance through more atmosphere. The muons that were calculated that did not have the effects of the energy loss do not show the low energetic muons. The do not lose energy as they propagate through the atmosphere, but reach the earth will all their initial energy. Due to this, the lower energetic muons are not present in this distribution. However for the energy range of 10 GeV to 100 GeV, the simulation shows more muons than both the calculated distributions. This means that in the simulations there are more high energetic muons reaching the earth than in the calculations.

Finally, the different models show substantial differences in figure 12 and figure 13. The different particles get treated differently for the same models in the energy range of 10 GeV to around 10 TeV. As can be seen in figure 13, the EPOS model creates the least of $\pi^+$ and $\pi^-$ in this energy range. However when looking at figure 12, the SIBYLL model is the one with the least amount in this energy range. The QGS model also makes around 10% less neutral pions than charged pions. One possible reason for this decrease of both models in this region could be the model that they are being compared to, which is the EPOS model. If the EPOS model would create more neutral pions in this energy range, it would look like as if the other two models would have a decrease in the number of muons in this energy region. So it could be that what looks like a difference in the SIBYLL and QGS model could actually be a difference in the EPOS model.

# 9 Conclusion

In this paper the behaviour of the pions in air showers has been discussed. The strict input parameters of the simulations results in not the most physically representative air showers, but it does allow the overall air shower behaviour to be studied. At first the neutral pions, where the dependency of the initial energy of the air showers was found. The average energy going into the creation of $\pi^0$ increases, while the average energy going into the muons decreases as the initial energy gets higher. This is a result of the charged pions traveling through the atmosphere and interacting with the atmosphere.

Secondly there is looked at the muons created from the charged pions that did not decay. Here, the difference between the chances of the muons reaching the ground with and without energy loss were shown. By using this energy loss and the interaction length of $\pi^\pm$ a model was created of counting the number of muons. This model yielded more muons than was predicted by the simulations. This could be due to the assumption that all the muons travel straight down and that the energy loss is fixed at 2 MeV per g $cm^{-2}$. It could be insightful to have a look at the number of muons when en not all the trajectories are perpendicular to the earth and with the use of the Bethe-Bloch formula for the energy loss of the muons. In addition the decay of $\pi^{\pm}$ into muons, other particles decaying into muons can also be taken into account.

The differences between the hadronic interaction models are most prominent for pions in the middle energy ranges=. There were also differences between the treatment of the neutral and charged pions by the same models, again in the middle energy range.

Furthermore, the initial energy dependency of the $\pi^0$ and muon energy percentages can be studied more in depth by looking at higher energies. The energy percentages in figure 5 appear to be reaching an asymptotical value. When looking at higher initial energies it can be determined whether this is the case.

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