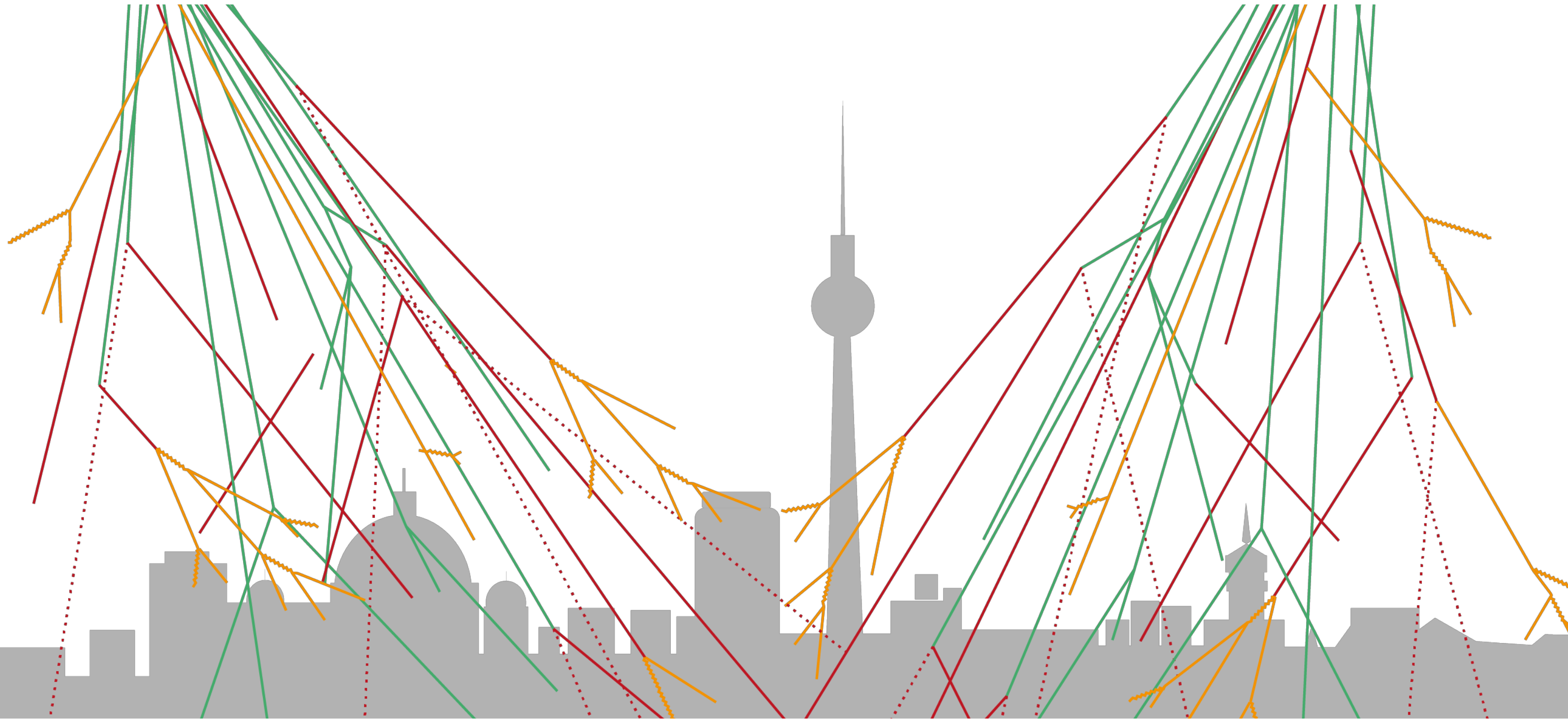
Zenith angle dependence of Cosmic muons



Measurement and analysis with the CosMO experiment and Cosmic@Web

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NETZWERK TEILCHENWELT

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1. Introduction

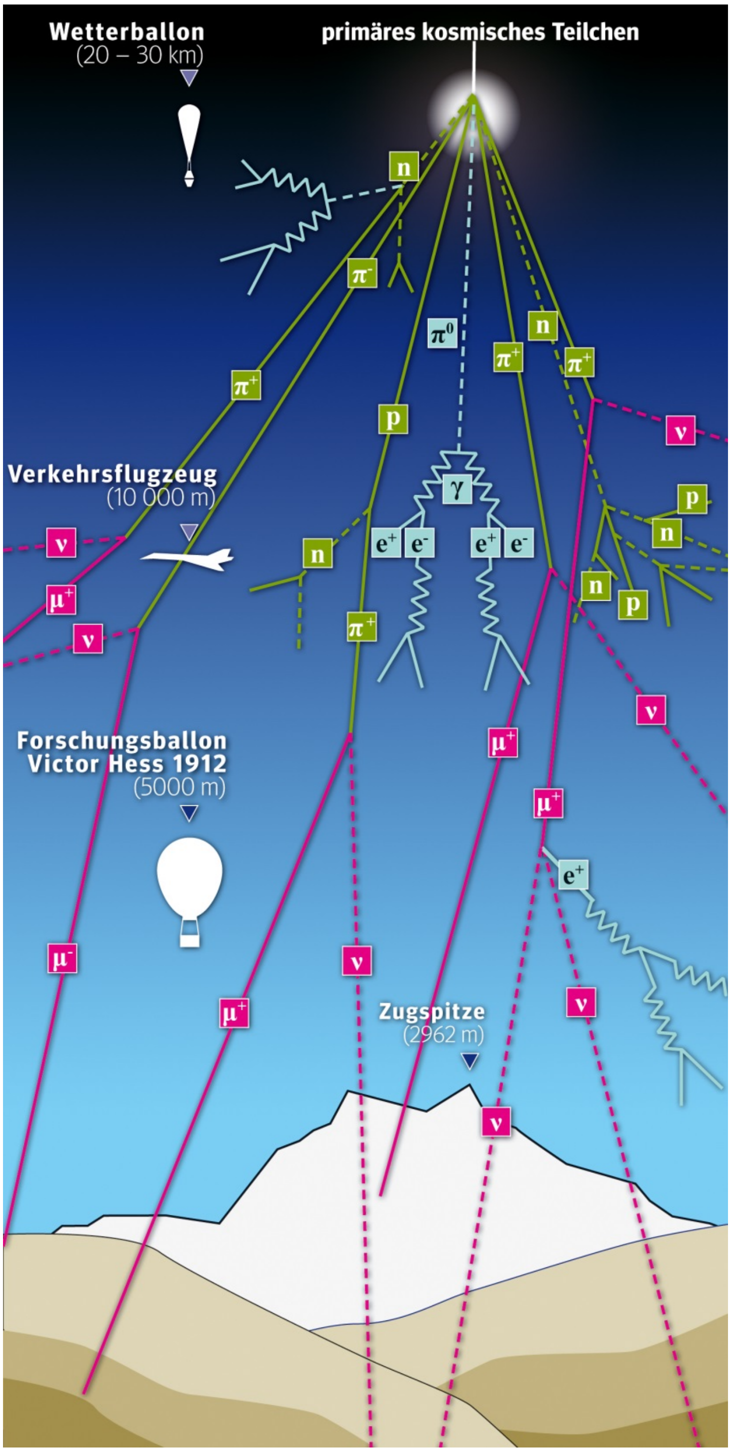

Fig. 1: Particle shower in the atmosphere

At sea level, the most abundant of the charged cosmic ray particles is the muon. Muons are usually produced as a decay product of pions from Cosmic Rays at a height of approx. 15 km[1]:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

The muon, one of the elementary particles, is the unstable "big brother" of the electron. It is negatively-charged and roughly 200 times heavier than the electron, into which it decays after its lifetime of 2,2 μs[2]. The reason that muons still reach the earth's surface is explained with the theory of Special Relativity. In the following, two possible investigations are presented that examine more closely muons and answer the following questions:

How often does a muon reach the ground?

Which direction do most muons come from?

Can the sun be proven as a source?

Are muons stopped by matter?

[1] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics - 29. Cosmic Rays.* S.422

[2] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics.* S. 32

2. The CosMO experiment and the muonic software

The Cosmic Muon Observer[3] is a scintillation counter. As soon as a charged particle passes through the detector, atoms in the scintillator are excited. When the atoms change from the excited state to the ground state, they emit photons. These are relayed via optical fibers to a multi-pixel photon counter, which turns the light signal into an electrical one. The time-dependent electrical signal is then processed by the data processing card (“DAQ card”).

With the muonic[4] software, the data-processing on the DAQ card can be controlled, and the measured values read out. The software can read detectors in coincidence, so that only simultaneous signals are evaluated. This makes it possible to distinguish muons from the natural ambient radiation and noise.

To investigate the rate of cosmic muons as a function of the zenith angle, at least two detectors must be installed at a fixed distance from one another. Using muonic, a coincidence measurement can be activated in “twofold”, or “threefold“ using three detectors. (The trigger rate corresponds to the number of events in which a signal was measured simultaneously).

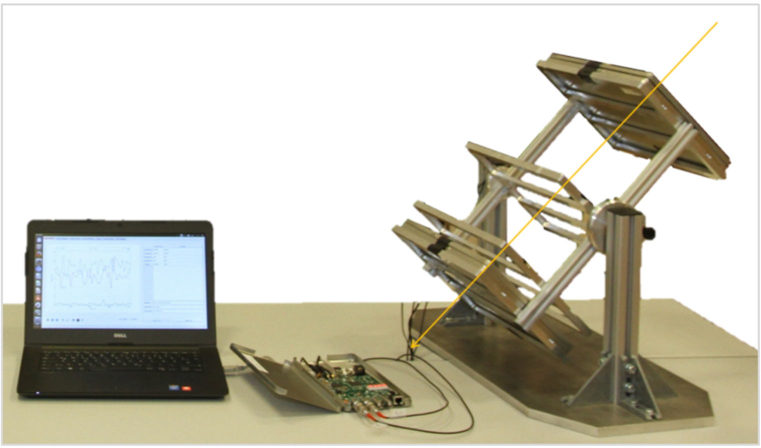

Fig. 2: Example of the measurement setup with a frame

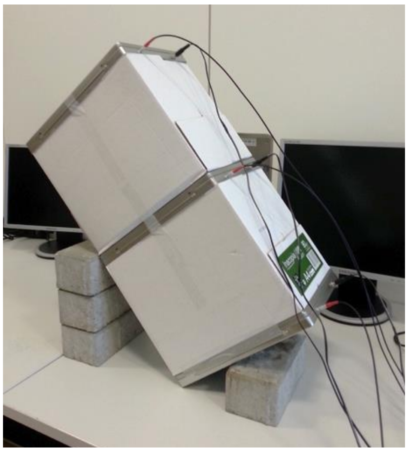

Fig. 3: Example of the measurement setup with boxes and bricks

The closer different detectors are placed to each other, the larger the aperture angle at which muons pass through both detectors and produce a trigger event. Using close detector spacing means that the zenith angle can only be resolved with limited precision. It can also lead to an overlap in the measuring range of the angle settings when the opening angle is greater than the distance between two adjacent measuring angles. If this is the case, muons can be measured coming from one direction with two different detector orientations. This leads to double counting. It is recommended that you estimate the opening angle and then choose the zenith angles accordingly.

[3] http://physik-begreifen-zeuthen.desy.de/angebote/kosmische_teilchen/schuelerexperimente/cosmo_experiment

[4] https://github.com/CosmicLabDESY/muonic

To investigate the zenith angle dependence of the muon rate, the trigger rate is measured and recorded at several zenith angles between 0° and 90°. The individual detector rates can also be noted. Even measuring at just a few different angles for 3 min each shows a clear trend, and allows conclusions to be drawn on the processes of formation and propagation of muons in the atmosphere. More measurement angles and a longer measurement duration of up to 30 min will provide sufficient data for a clear distribution, which matches the expectations of the literature[5].

2.1. Evaluation of the data with a spreadsheet program

The values measured with the CosMO experiment can be displayed with a spreadsheet program such as Excel. It must be ensured that the corresponding notation for the decimal point is used, depending on the German or English language program.

	Rate in Hz				
Zenith angle in Grad	**chan0**	**chan1**	**chan2**	**trigger**	**0,5 cos²**
0°	7,13	8,19	7,63	0,57	0,5
15°	6,82	7,71	6,98	0,52	0,47
30°	6,5	7,91	6,47	0,41	0,37
45°	6,03	7,17	6,16	0,31	0,25
60°	5,14	6,49	5,27	0,13	0,12
90°	4,44	6,49	4,72	0,03	$6*10^{-12}$

Fig. 4: Measurement with three CosMO detectors and a measuring time of 5 min per angle

The diagram below is a processing of the data with Excel. A $\cos^2$ curve was placed over the trigger rate curve for comparison.

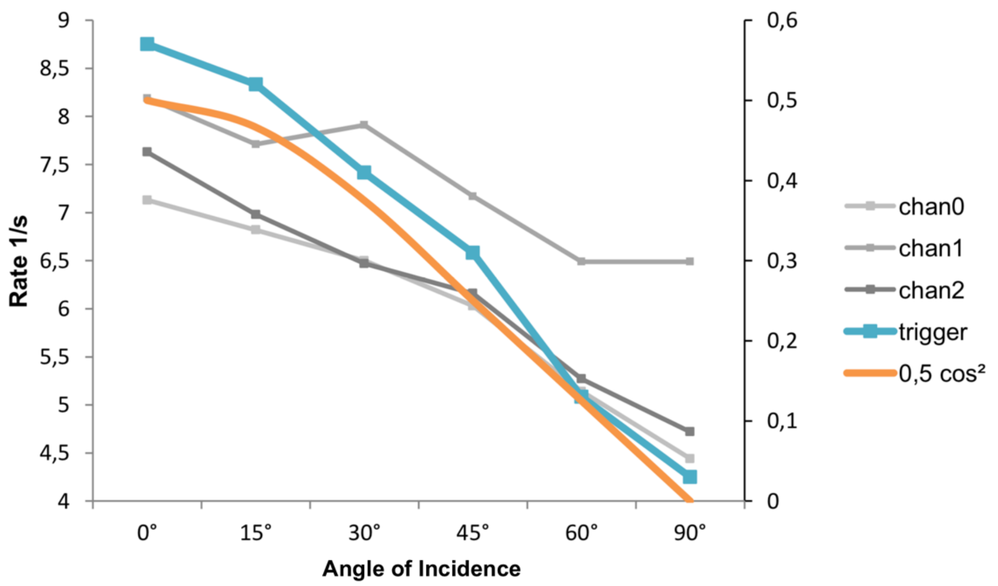

Fig. 5: Processing of the data with Excel

[5] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics - 29. Cosmic Rays.* S.423

The decrease in the trigger rate with increasing zenith angle is clearly visible. A discussion of the evaluation of the trigger rate is given in chapter 4.

If the individual detector rates are included in the analysis, it can be seen that they also change relative to the overall coincident trigger rate. This can be understood when the measuring principle of the individual detectors is considered more closely.

A detector measures muons coming from all directions. A change in detector orientation should not affect the rate measured from the incoming muon flux. However, the detector has a larger footprint when viewed head-on rather than side-on. If the larger base area is rotated in the direction of lower, horizontal muon flux, there is a smaller detector surface overlapping with the abundant vertically incident particles. The decrease of the individual detector rates thus reflects the change in the detector geometry in connection with the zenith angle dependence.

2.2. Evaluation of the data with Python

You can also use a self-written script in Python to display the data. The following is an example:

```
import matplotlib.pyplot as plt
import numpy as np

deg=[0,15,30,45,60,90]
rate=[0.57,0.52,0.41,0.31,0.13,0.03]

area=90
x=np.arange(area)
y=0.57*np.cos(x/180.0*np.pi)**2
plt.xlabel('Messwinkel in deg')
plt.ylabel('Rate in Hz')
plt.plot(deg, rate,
      color='b',
      linewidth=2,
      linestyle='-',
      label='trigger')
plt.plot(x, y,
      color='r',
      linewidth=1,
      linestyle='--',
      label='cos^2-Fit')
plt.legend()
plt.show()
```

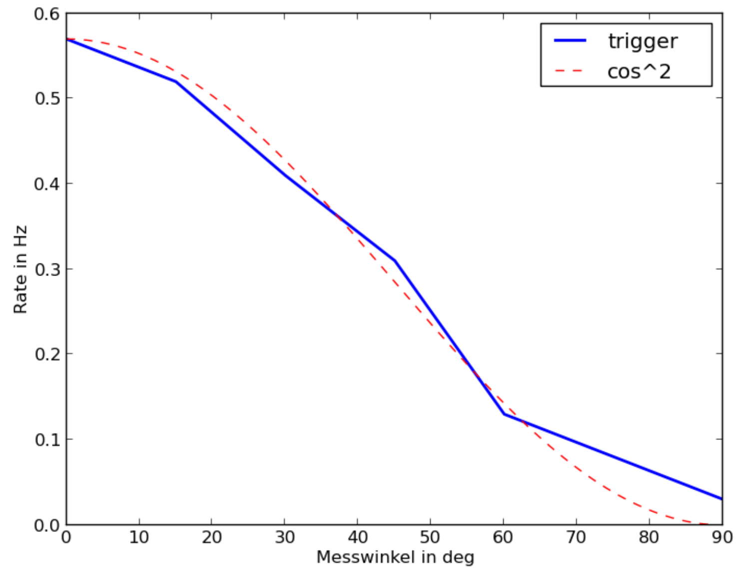

Fig. 6: Processing of the data with Python

3. The CosMO-Mill and the web platform Cosmic@Web

The CosMO-Mill[6] consists of a rotatable frame which, driven by a stepper motor, changes position every hour by 15° within an interval of -90° to 90°. In one day the mill arm thus completes one full cycle. The Mill is facing west-east.

The two CosMO detectors, mounted at a distance of 97 cm, are read in coincidence. Due to the larger distance compared to a standard test setup, the opening angle of the experiment is reduced and a more accurate directional determination of the particles is thus made possible.

Data is continuously taken with the muonic software, which can then be analyzed via Cosmic@Web.

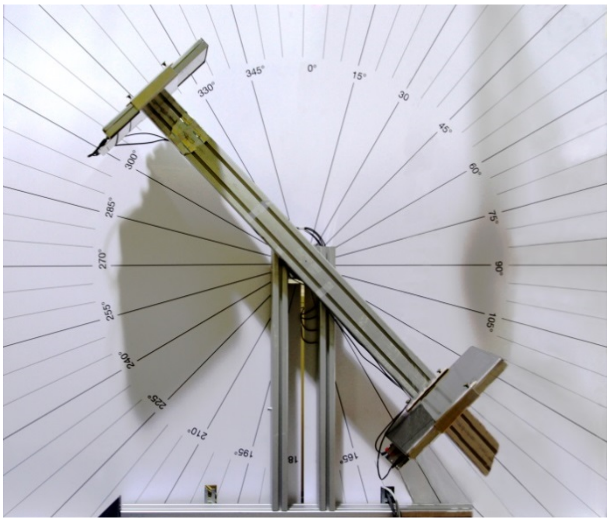

Fig. 7: Photograph of the CosMO-Mill

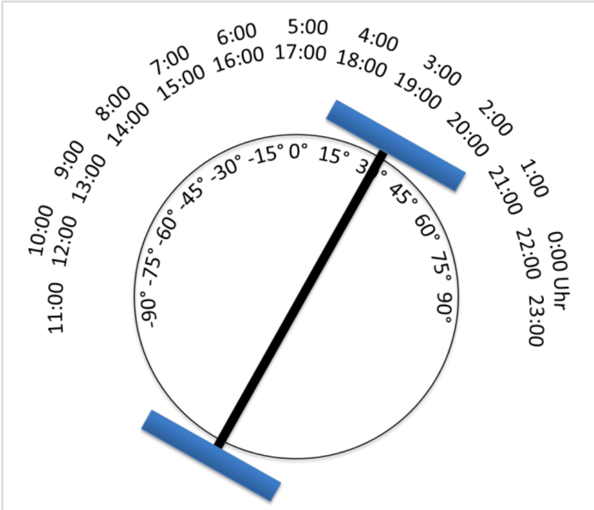

Fig. 8: Exemplary schematic representation of the measuring sequence of the CosMO-Mill

The web platform Cosmic@Web[7] provides long-term data sets from several astroparticle experiments, as well as data analysis tools. It is modelled on modern scientific practices, with data being retrieved from a server and analyzed locally on a computer. At any time, independent of location, the data can be retrieved via Cosmic@Web and evaluated in diagrams with your own settings. A detailed description of the elements available for viewing and analyzing the data on Cosmic@Web can be found in the How To[8].

The CosMO-Mill data on Cosmic@Web contain values for time, muon rate, zenith angle, atmospheric pressure and temperature. The data is documented in detail in the description of the dataset[9]. Various analyses are possible, such as the evaluation of the rate of cosmic particles as a function of the zenith angle, the study of the influence of weather conditions on the rates at different angles, the comparison of the data at different times or the comparison with data from other experiments.

[6] http://physik-begreifen-zeuthen.desy.de/angebote/kosmische_teilchen/cosmicweb/cosmo_muehle
[7] https://physik-begreifen-zeuthen.desy.de/angebote/kosmische_teilchen/cosmicweb
[8] http://physik-begreifen-zeuthen.desy.de/angebote/kosmische_teilchen/cosmicweb/how_to
[9] http://physik-begreifen-zeuthen.desy.de/angebote/kosmische_teilchen/cosmicweb/cosmo_muehle/datenstruktur

3.1. Evaluation of data with Cosmic@Web

Cosmic@Web offers its users two modes that allow different settings. The *Standard* mode makes it easy and fast to get started, with setting reduced to only the essentials (alongside a helpful tutorial to explain the features). In the *Detailed* mode, the analysis of the data can be refined and the presentation of the diagram can be adapted to your own requirements.

3.1.1. Muon rate as a function of angle

In order to investigate the dependence of the muon rate on the selected measurement angle, a representation with an xy diagram using the following settings is recommended:

Data Set: 20160509-20160518_M – rate per angle
Diagram Type: xy-Diagram
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
Symbol Size: 10

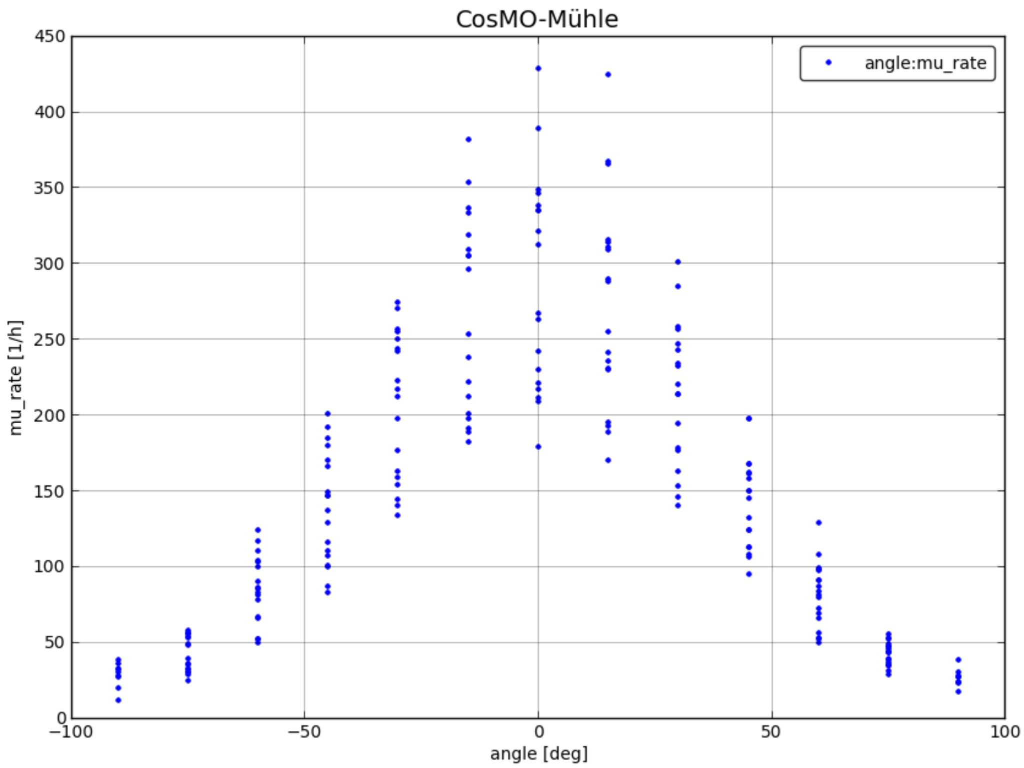

Fig. 9: Investigation of the zenith angle dependence with Cosmic@Web

It can be clearly seen that the highest rates were measured at zenith, and that the particle rate continuously decreases as the zenith angle increases. An increased dispersion of the measured values in the muon rate is also observed at smaller zenith angles.

Due to the scaling of the y-axis, this scattering is more clearly visible at measuring angles of 0°, and less visible at measuring angles of 90° or -90°. Thus, the values at 0° vary from 175 and 440 particles per hour, at -60° from 80 to 200 particles per hour. However, the deviation from the mean value of the measured rate is around 42% at all measurement angles. It is suggested that these variations in muon rate can be attributed to changing atmospheric influences such as atmospheric pressure and temperature.

In order to produce a plot comparable to Fig. 5 and 6, the following settings can be used:

Data Set: 20161012-20161016_M – rate per angle
Diagram Type: xy-Diagram
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
Fit Function: p[0]+p[1]*cos(pi*(p[2]*x+p[3]))**2
Start Parameters: 33.3,425.5,0.00576,-0.0104
x-Axis Start Value: 0
x-Axis Maximum Value: 90

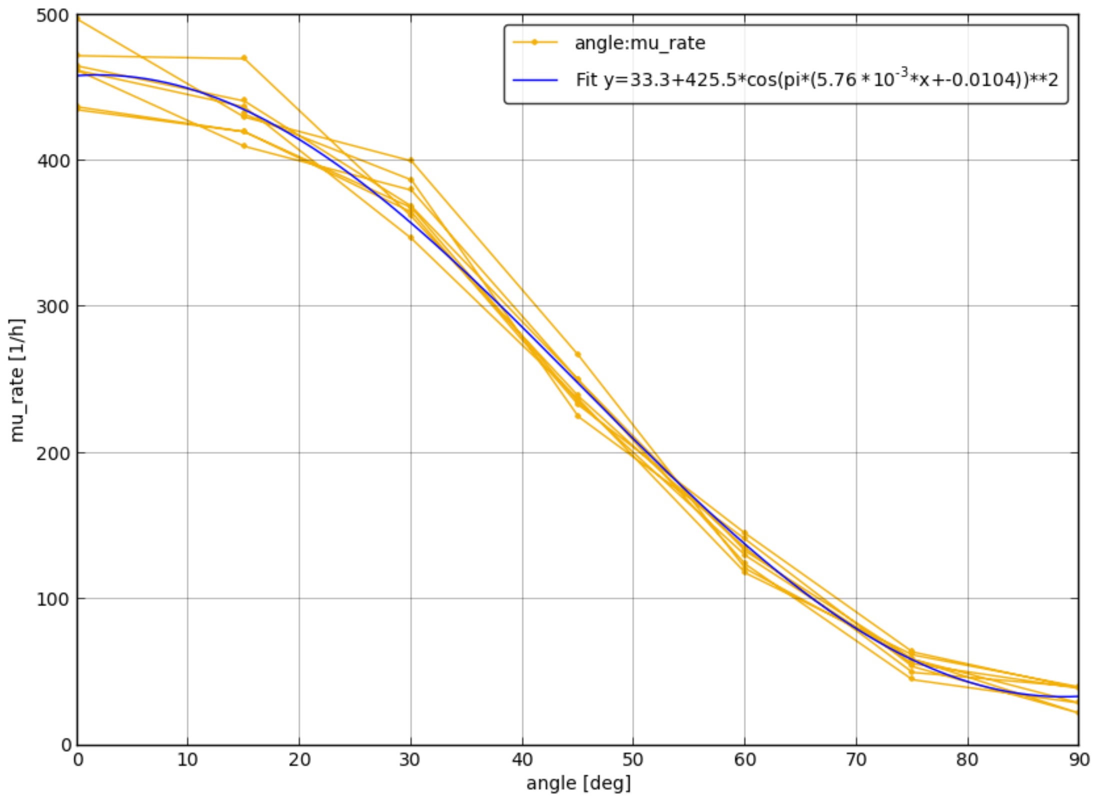

Fig. 10: Investigation of the zenith angle dependence with Cosmic@Web in the range from 0° to 90°

In the diagram, the measured values are plotted in the range from 0 ° to 90 °. The individual measured values were connected by a line in chronological order. In addition, a cos2 fit was determined. To determine this fit, i.e. to find a mathematical description of the measured values with the smallest possible error, a general fit function with estimated start parameters must be specified in Cosmic@Web. The legend shows the best fit.

An evaluation of the analysis can be found in chapter 4.

3.1.2. Fit function

For the angular dependence of the muon rate, a $\cos^2$ distribution is expected[10]. To create such a fit with Cosmic@Web, the following should be noted:

The general form of the $\cos^2$ function is: $y = a * \cos(bx + c)^2 + d$

The notation in the program is: p[0]+p[1]*(cos(pi*(p[2]*x+p[3])))**2

**2 stands for the power, so for example x^2. The parameters p[0] to p[3] influence the following properties:
p[0] .. (=d) vertical shift
p[1] .. (=a) vertical stretch
p[2] .. (=b) horizontal stretch
p[3] .. (=c) horizontal shift

3.1.3. Atmospheric pressure of the muon rate

In order to investigate the dispersion of the measured values more precisely, especially in the measuring range around 0°, the measured rate can be examined as a function of the atmospheric pressure. Cosmic@Web offers to set an additional z variable as a color scale and thus allows you to investigate the dependency of three variables in one plot. The following settings have been selected for this:

Data Set: 20160518-20160704_M – rate per angle
Diagram Type: XY-Diagramm
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
z-Variable: p [mbar]
Condition: 2347<=(time/(24*60*60))<=2358
Symbol Size: 10

[10] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics - 29. Cosmic Rays.* S.423

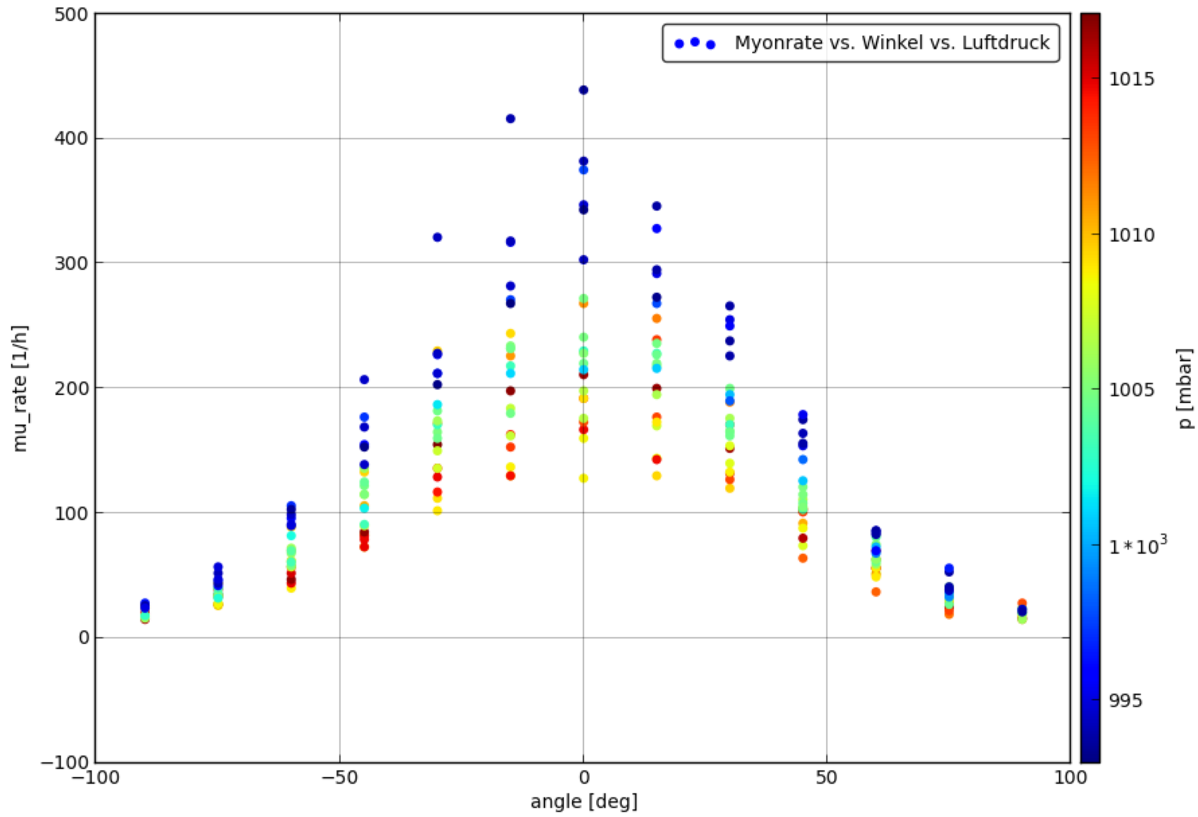

Fig. 11: Investigation of the atmospheric pressure dependence of cosmic muons

In this xy diagram, the trigger rate is plotted for each measurement angle. The color of the prevailing atmospheric pressure at the time of measurement is colored. For analysis, a time vs. atmospheric pressure diagram was used to determine and select only a specific period, which includes one phase with a rather high atmospheric pressure and another with a rather low atmospheric pressure. The condition 2347<=(time/(24*60*60))<= 2358 limits the statistics to 12 days.

The graph suggests that the dispersion of muon rate readings is correlated with atmospheric pressure changes. At higher atmopsheric pressure the rate tends to be lower, while at a lower atmospheric pressure it tends to be higher. This relationship can be explained by the fact that with higher atmospheric pressure charged pions become more likely to interact and less likely to decay. Muons are produced when pions decay. When charged pions interact, new pions with less energy are created. When these lower-energy pions eventually disintegrate, muons are created with less energy. Their energy is then too low to reach the ground, meaning that overall the muon rate is anti-correlated with the atmospheric pressure.

3.1.4. Time dependence of the muon rate

The data can also be analyzed as a function of time. The variable "time" contained in the data set indicates the time as seconds since January 1, 2010 at 00:00 (UTC). A conversion in hours is possible with the help of a correction function. The following is an example of possible settings:

> Data Set: 20161012-20161016_M – rate per angle
> Diagram Type: xy-Diagramm
> x-Variable: time [s]
> Correction Function for x-Variable: time/(24*60*60)
> y-Variable: mu_rate [1/h]
> Fit Function: p[0]+p[1]*(cos(pi*(p[2]*x+p[3])))**2
> Start Parameters: 20,200,2,0.05

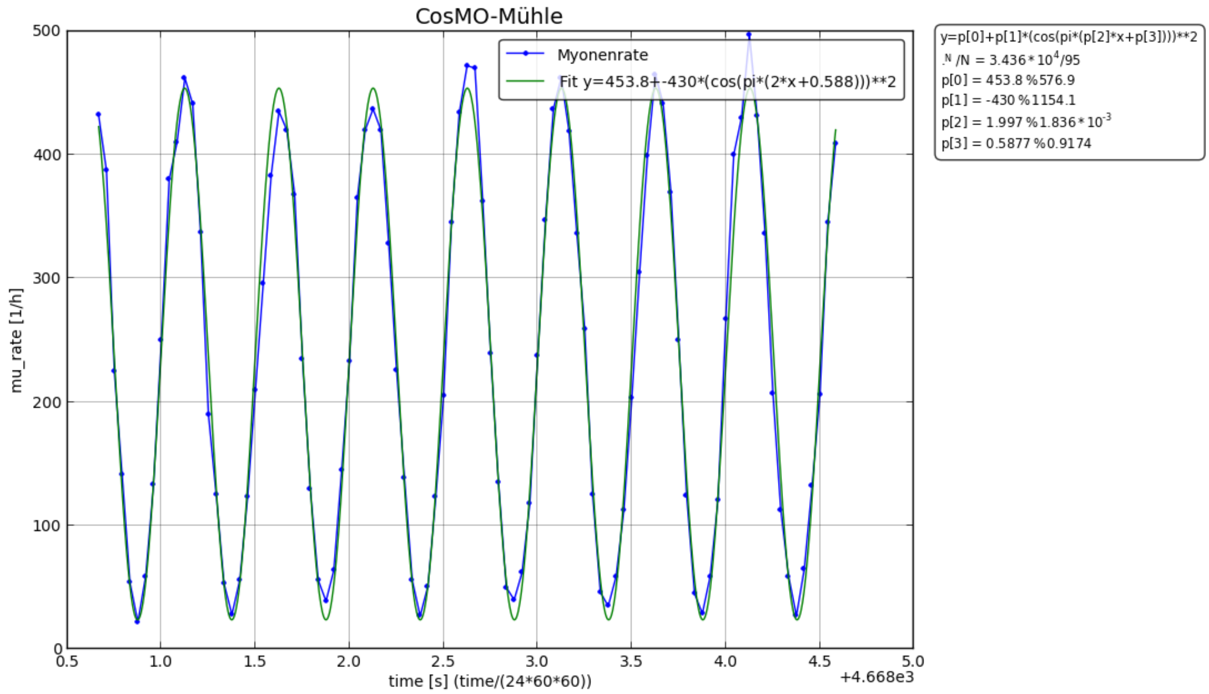

Fig. 12: Investigation of the muon rates measured by the CosMO-Mill over time

To interpret this diagram, the hourly rotation of the experimentation setup must be taken into account. The time on the x-axis was converted from seconds to days using the correction function time/(24*60*60). The fluctuations clearly form a sinusoidal pattern. A square cosine is suitable as a fit function. Only at the high and low points are there slight deviations, which can be attributed to weather conditions.

Even with this form of graph, the expected zenith angle dependence can be observed. In addition, the regular rotation of the experimentation setup can be retraced.

4. Analyzing and understanding the distribution

The rate of cosmic particles reaches a maximum value at zenith, and continually decreases at increasing zenith angles. At 90° the rate is minimal. As it can be found in "Review of Particle Data"[11], the distribution of the measured values can be described using a cos² function. Different effects are responsible for this, the former having the greatest influence.

Path through the atmosphere

If secondary cosmic particles like pions decay at an altitude of about 15 km, muons are produced. These are unstable particles and have an average life of 2,2 µs. With classical mechanics, we can calculate using $v = \frac{s}{t}$ that muons should travel only about 660 m before decaying[12].

However, since muons move at nearly the speed of light, the special theory of relativity must also be considered. As a result of "time-dilation" arising from its high velocity, the time for a near-speed-of-light muon passes more slowly, so that it is able to cover the distance of 15 km. In fact, the time dilation/ length contraction allows the muons to cover an average distance of 33 km.

With a larger angle of incidence, the distance from the place of origin of the muons in the atmosphere to the detector on the earth's surface is extended. At an angle of incidence of 90°, the distance the muon has to travel through the atmosphere to the surface of the earth is about 400 km. Only a few high-energy muons manage to cover this path.

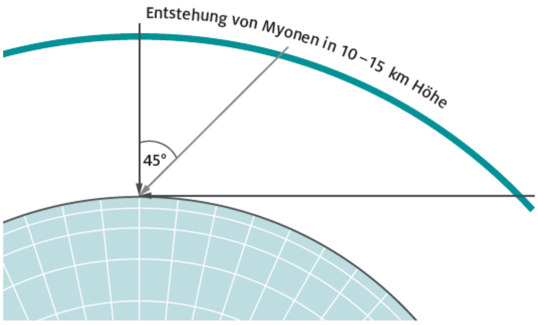

Fig. 13: Path of muons through the atmosphere

Dependence of the direction of incidence of the pions

Due to the conservation of momentum, muons continue to move in the same the direction as their parent pions. The probability of decay or interaction of a pion depends on the mean free path. When a pion hits the atmosphere head-on, it quickly reaches the denser lower atmosphere, where there are many more particles to interact with. The likelihood of an interaction is then high, and more pions are produced. The energy of one pion is divided among the resulting pions. If their energy is so low that a decay becomes more likely than another interaction, they decay into muons.

When pions enter the atmosphere at a larger angle, an interaction becomes less likely due to the lower density and thus less available interaction partners. If a charged pion does not interact, it decays into a muon and a neutrino after just 0,028µs[13]. Due to the energy

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[11] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics - 29. Cosmic Rays.*

[12] Rechenbeispiel siehe: Joachim Herz Stiftung in Kooperation mit Netzwerk Teilchenwelt (2016): *Teilchenphysik, Unterrichtsmaterialien ab Klasse 10, Kosmische Strahlung.* S. 21

[13] C. Patrignani et al. (Particle Data Group), Chinese Physics C, 40, 100001 (2016): *Review of Particle Physics.* S. 32 S. 37

conservation, it transfers all of its energy to the muon and the neutrino. These muons receive more energy than those produced from pions that interact several times.

5. Errors and limitations of the measurement

Systematic Error

In the data processing of the trigger for CosMO and the CosMO mill, there is a condition that an event is evaluated as a trigger if a signal is measured within a short period of time (standard 100ns) in all required detectors. If the experimental setup is oriented towards the zenith, only muons from above can pass the detector because the earth acts as a filter. When the experimental setup is rotated, more and more horizon-skiing muons can pass the detector, although muons from this direction are very rare.

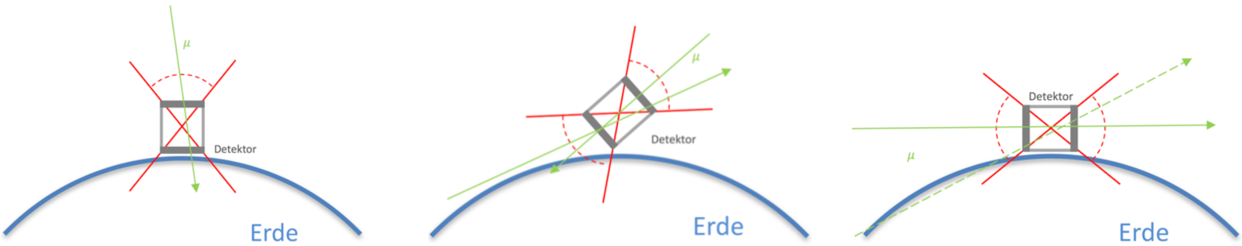

Fig. 14: Angle of aperture of detector configuration and associated trigger possibilities of incident muons

If the setup is oriented towards the horizon, it is very likely that muons will pass through the experiment from both sides (from "below" and from “above"). However, the aperture angle of the experiment is now reduced by the absorbing effect of the earth. Thus the systematic error increases with increasing zenith angle.

Statistical error

If the measurement duration is not adapted to each measurement angle, this results in varying statistical errors. The measurement of muons corresponds to a poisson-distributed process. The error on such a poisson-distributed statistic is $\sqrt{N}$, where N is the number of events per measurement. Accordingly, the measurement of more and more events leads to an ever smaller relative error. The statistical error for 0° degrees is therefore comparatively small, since a high rate is accompanied by a high statistic and thus a more accurate value has been determined. If the measurement duration is left the same for all angles, then 90 ° significantly fewer events will be measured, so the error on these values will be greater.