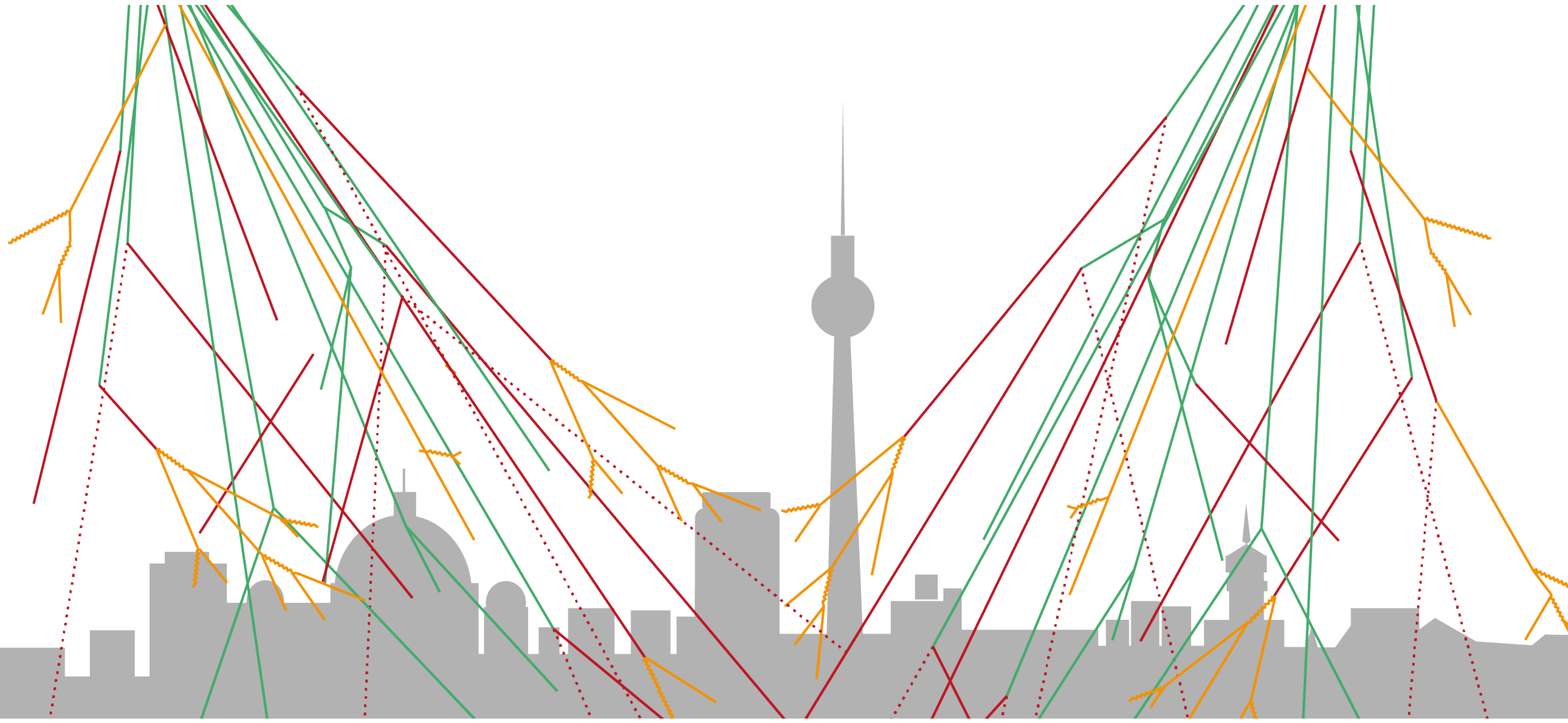
Zenith Angle Dependence of the Cosmic Muon Rate



Measurement and Analysis with Cosmic@Web

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1. Introduction

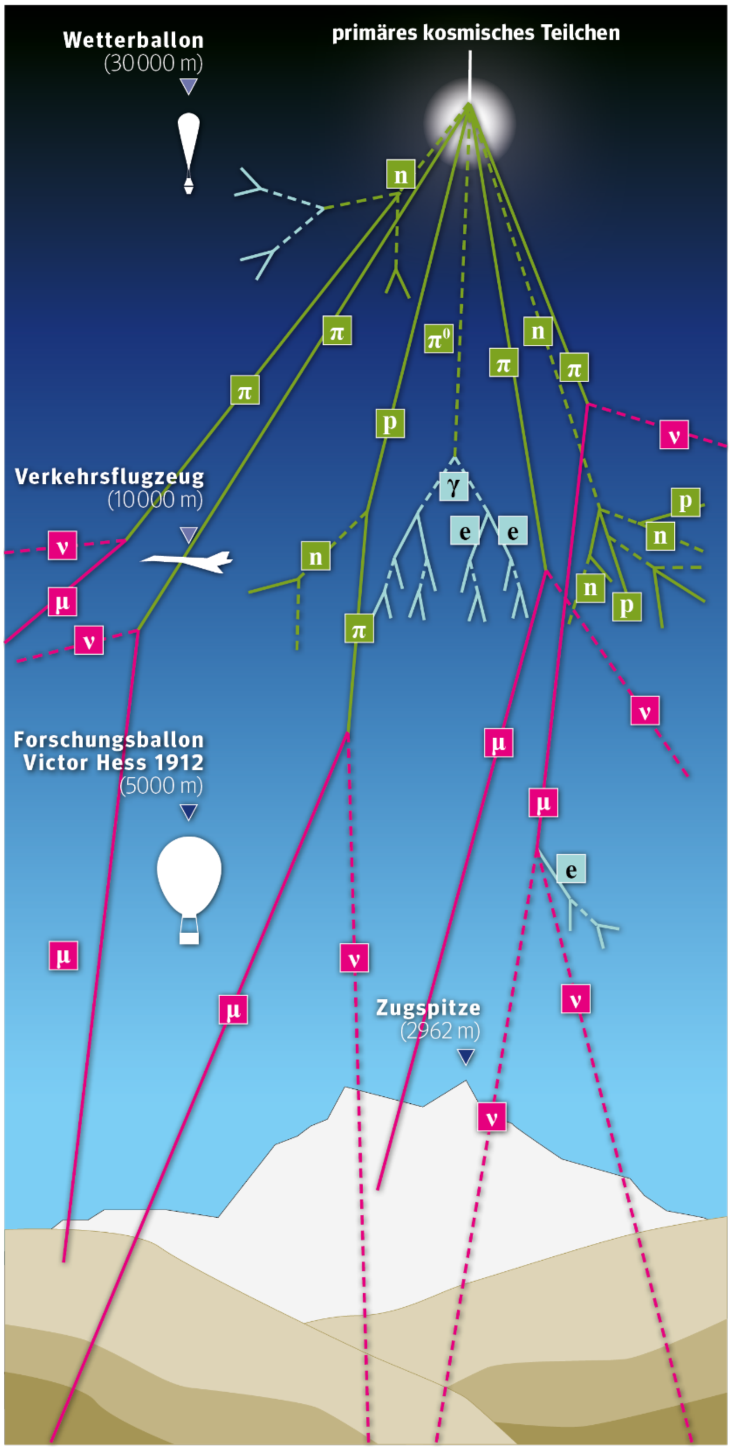

Fig. 1: Particle shower in the atmosphere

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, a possible investigation is presented that examines muons more closely and answers 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-Mill and the Web Platform Cosmic@Web

The CosMO-Mill[3] 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, allowing a more accurate directional determination of the particles.

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

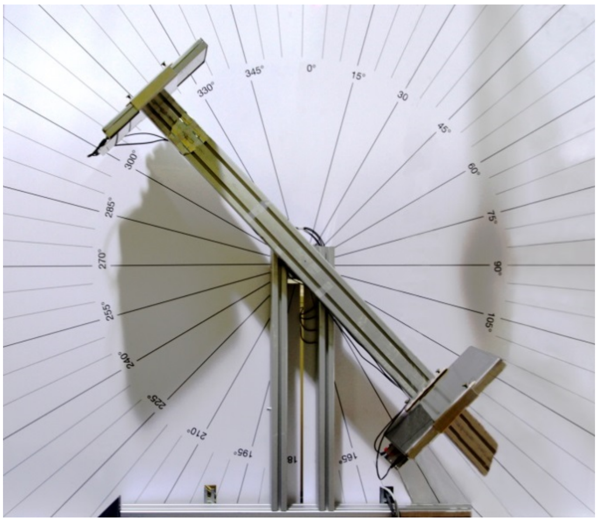

Fig. 2: Photograph of the CosMO-Mill

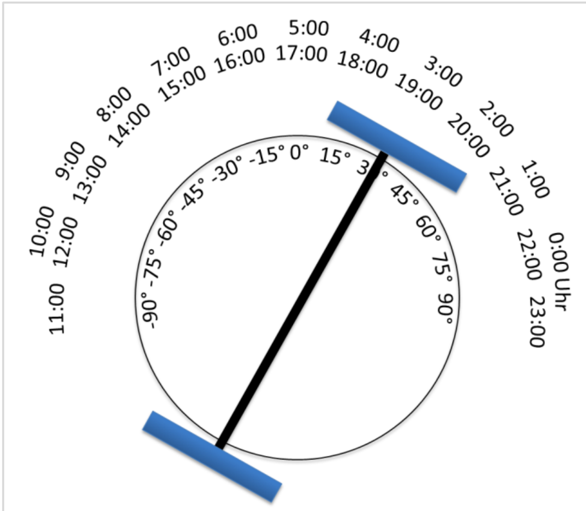

Fig. 3: Exemplary schematic representation of the measuring sequence of the CosMO-Mill

The web platform Cosmic@Web[4] 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 Documentation[5].

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[6]. 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.

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3 https://www.desy.de/school/school_lab/zeuthen_site/cosmic_particles/experiments/cosmo_mill/index_eng.html

4 https://www.desy.de/school/school_lab/zeuthen_site/cosmic_particles/cosmicweb/index_eng.html

5 https://www.desy.de/school/school_lab/zeuthen_site/cosmic_particles/cosmicweb/documentation/index_eng.html

6 https://www.desy.de/school/school_lab/zeuthen_site/cosmic_particles/experiments/cosmo_mill/e288712/index_eng.html

3. 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 settings 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. Muon rate as a function of angle

In order to investigate the dependence of the muon rate on the selected measurement angle, it makes sense to use an xy-diagram. The following settings will lead to a suitable diagram of a measurement between the 9th and the 18th May 2016:

Dataset: 2016_M – rate per angle
Plot Type: xy-Plot
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
Condition: 2016050900 <= ymdh <= 2016051823
Symbol Size: 10

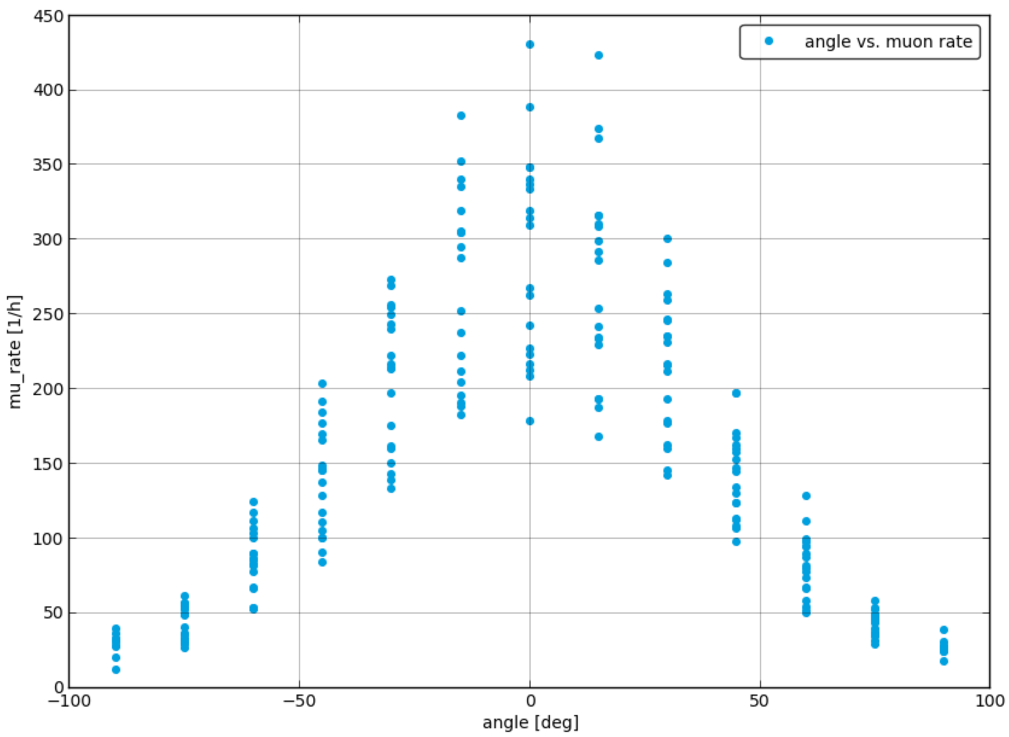

Fig. 4: Investigation of the zenith angle dependence with Cosmic@Web

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 to 440 particles per hour, at -45° 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.

For the following evaluation it makes sense to display an even shorter time period of four days in order to filter out major weather fluctuations. The following settings can be used to create a suitable diagram of a measurement between the 12th and the 16th October 2016:

Dataset: 2016_M – rate per angle
Plot Type: xy-Plot
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
Condition: 2016101200 <= ymdh <= 2016101623
Fit Function: p[0]+p[1]*cos(p[2]*x/180*pi)**2
Start Parameters: 30,450,1
x-Axis Start Value: 0
x-Axis Maximum Value: 90

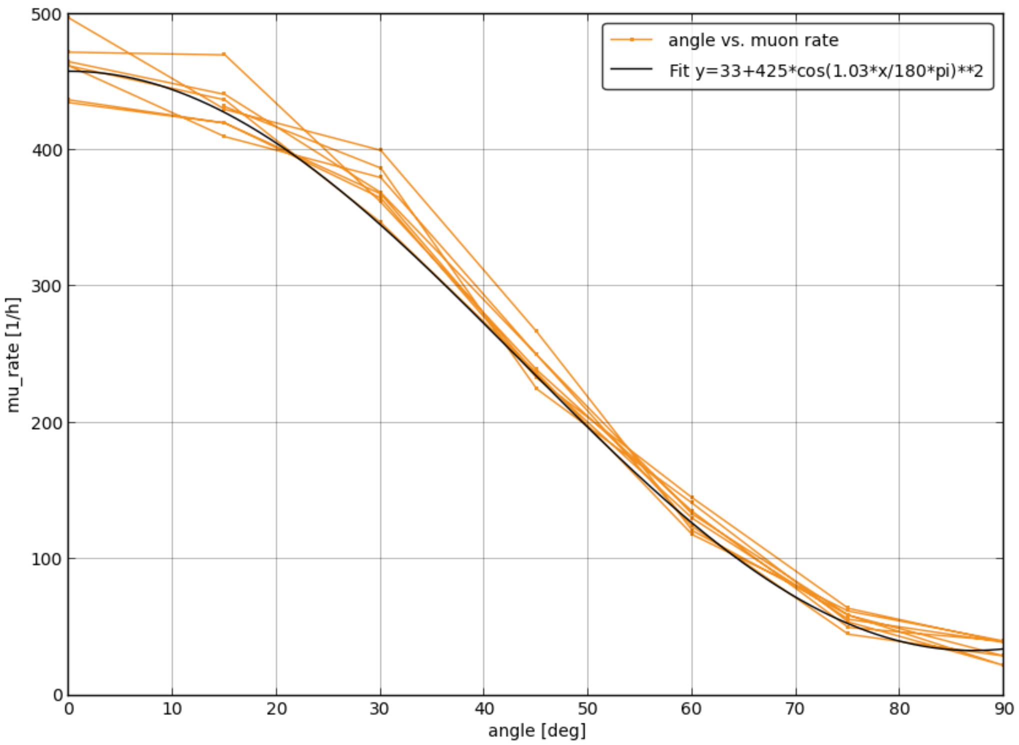

Fig. 5: Investigation of the zenith angle dependence with Cosmic@Web in the range from 0° to 90°

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 cosine square 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.

3.2. Fit function

For the angular dependence of the muon rate, a cosine square distribution is expected.[7] To create such a fit with Cosmic@Web, the following should be noted:

We use the following form of the $\cos^2$ function: $f(x) = a + b \cdot \cos\left(c \cdot \frac{\pi}{180} \cdot x\right)^2$

The notation in the program is: p[0]+p[1]*cos(p[2]*x/180*pi)**2

The parameters p[0] to p[2] influence the following properties:

p[0] $= a$ minimum of the distribution
p[1] $= b$ peak-to-peak amplitude
p[2] $= c$ phase

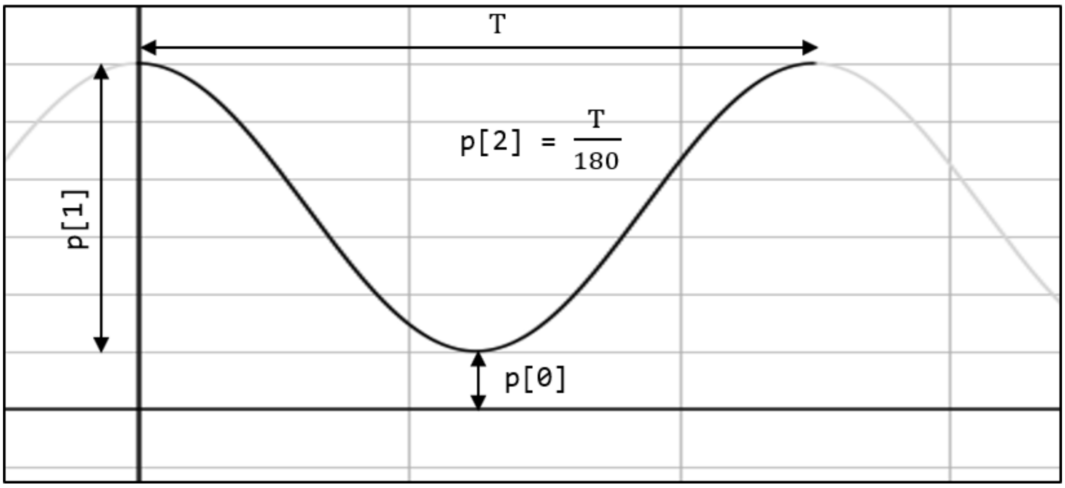

Fig. 6: Coefficients of the cosine square function

3.3. 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:

Dataset: 2016_M – rate per angle
Plot Type: xy-Plot
x-Variable: angle [deg]
y-Variable: mu_rate [1/h]
z-Variable: p [mbar]
Condition: 2016060400 <= ymdh <= 2016061623
Symbol Size: 10

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

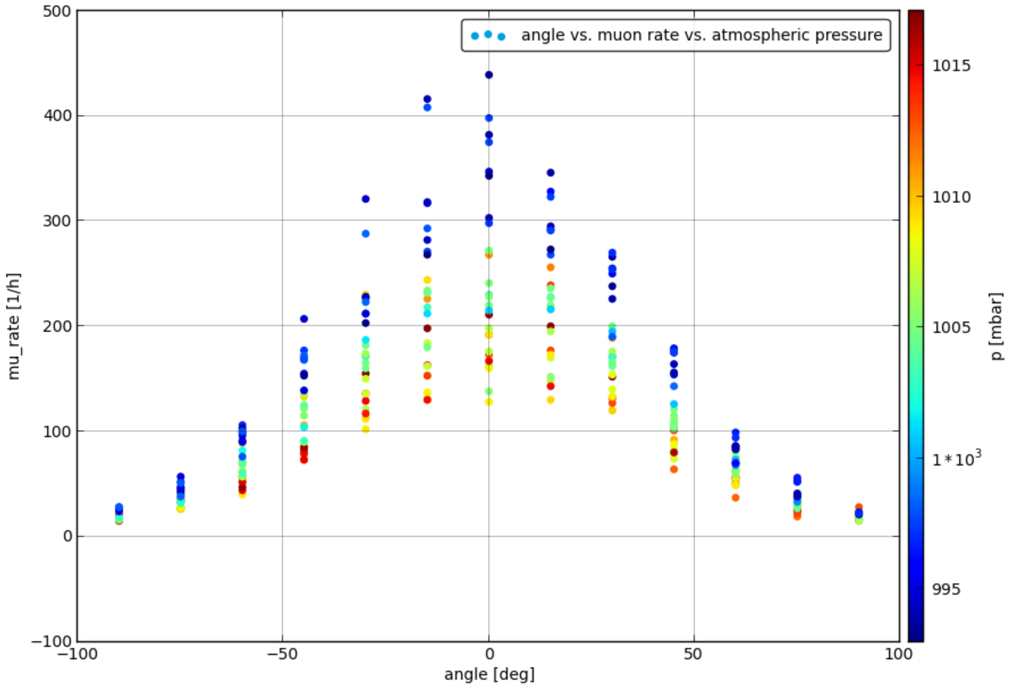

Fig. 7: Investigation of the atmospheric pressure dependence of cosmic muons

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 2016060400 <= ymdh <= 2016061623 limits the statistics to 12 days.

The graph suggests that the dispersion of muon rate readings is correlated with atmospheric pressure changes. At higher atmospheric 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.

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”[8], 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 $\mathrm{v} = \frac{s}{t}$ that muons should travel only about 660 m before decaying[9].

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.

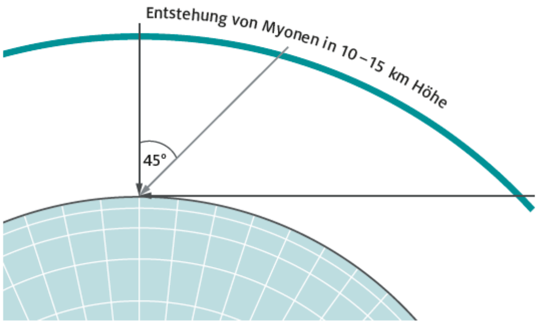

Fig. 8: Path of muons through the atmosphere

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[10]. Due to the energy

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

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

[10] 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.

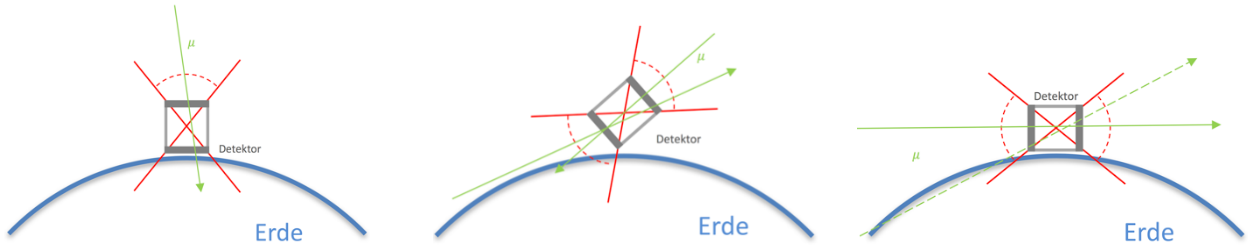

Fig. 9: Angle of aperture of detector configuration and associated trigger possibilities of incident muons

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 even 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.