Universität Freiburg
Advanced physics lab , part 1
Holiday internship in the summer semester 2024

Experiment 1
Cosmic muons

[redacted]
(Group 11)

November 5, 2024

Dates of experimental execution: August 23rd and 26th, 2024
Tutor: [redacted]

Contents

1 Goal of the experiment

The goal of this experiment is to measure the muon flux as a function of the zenith angle, the effect of shielding on the muon flux and the muon flux from the entire visible sky.

2 Experiment

The experiment is set up and executed as in the Experiment Guideline[1] on ILIAS mentioned.

2.1 Setup

For the experiment two identical scintillators are mounted on a metal rod. Their distance can be adjusted and the zenith angle θ of the rod can be set from $0°$ to $90°$ relative to the vertical axis, as illustrated in fig. 1. The scintillator Tiles are connected via a coincidence module to a PC, where the data is processed and saved with the CosmicHunter software.

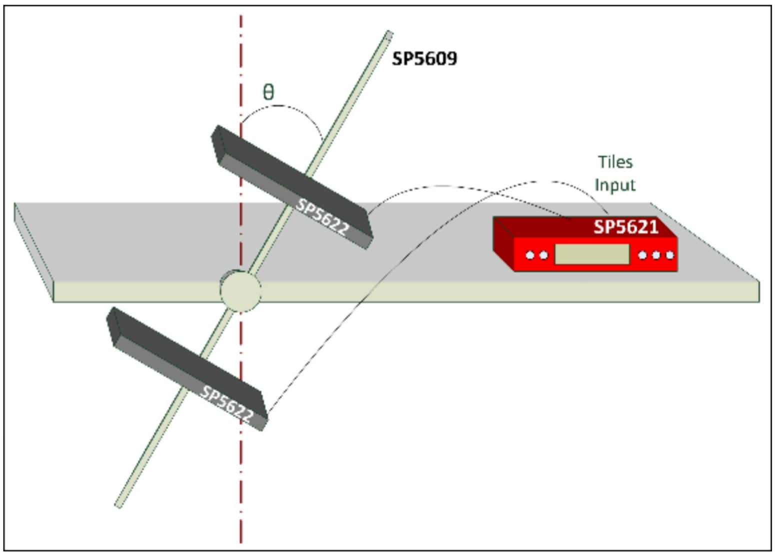


Figure 1: Setup [Edu21]

For the measurement of the random coincidence a different setup is used. It consists of the same two scintillators but placed in the same height, side by side (Illustrated in fig. 5 in the attachment). The scintillators had a horizontal distance of approximately one meter, so that the chance of true coincidence or even muons going through both scintillators is close to zero.

[1] [Wei]

2.2 Execution

There were several different measurements taken. At first, it was measured what probability distribution fits to the events of this setup. Therefore the setup was set to 0° and every eleven seconds the coincidences where noted.

The next measurement, the measurement for the random coincidence, was taken in the other mentioned setup. The measurement itself is made with the same software with an integration time of one hour. It counts the events automatically and saves a file with all collected data at the end.

Now the system is set to an integration time of 30 minutes and several measurement were performed, in the form shown in fig. 1. Those Measurements were done in varying zenith angles and in varying places. On top of the physics high-rise, in the basement two storeys under ground level and in the first floor lab of the Gustav-Mie-Haus.

For the last experiment the vertical distance between the detectors is minimized in 3 steps and the integration time of the measurement is ten minutes.

3 Evaluation and error analysis

3.1 Probability Distribution of muon flux

With a measuring time of $t = 11\,\mathrm{s}$ the counts are measured $n = 100$ times and illustrated in fig. 2. The bar chart is fitted with a Poisson distribution.

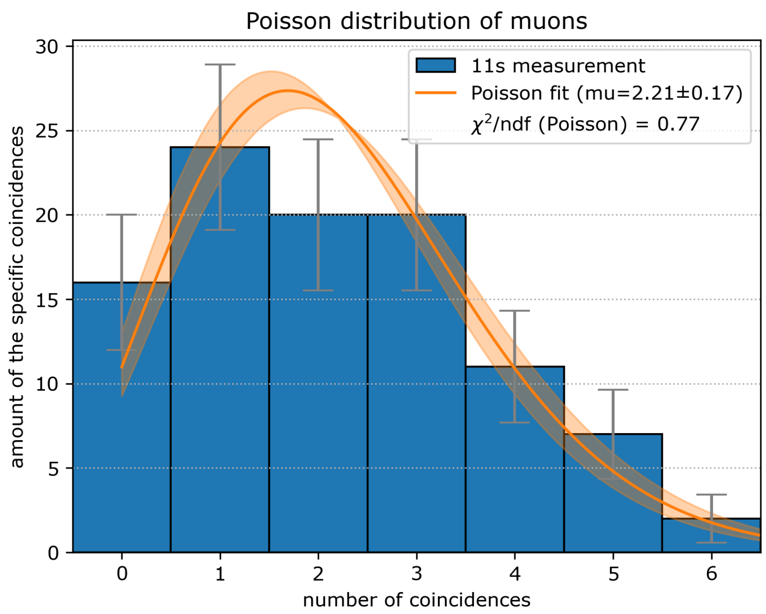


Figure 2: Probability distribution of counts

The quality of the fit is checked by adjusting two parameters out of seven. This leads to

$$\frac{\chi^2}{ndf} \approx 0.77,$$

so the quality of the measurement is good. So it is possible to say, the muon flux is Poisson distributed. The error bars come from the Poisson distribution with $\Delta x = \sqrt{x}$. This will be later the statistical uncertainty off all measurements.

3.2 Random Coincidence

For this measurement a different setup is used. The two scintillators are positioned around 1 m apart from each other and lay flat on the table. The Random Coincidence describes events, that trigger both scintillators at the same time, with no single particle cause. In the measuring time $t = 3600\,\mathrm{s}$, $A_A = 16239$ are the counts from scintillator A in the lab, $A_B = 15806$ those from scintillator B and $A_{Random} = 11$ is the random coincidence. The rates R are calculated by $R = \frac{A}{t}$ and the pulse duration τ is calculated by the formula

$$\tau = \frac{R_{Random}}{2R_A R_B}.$$

With $\Delta A = \sqrt{A}$ the errors ΔR_x result through the Gaussian error propagation to

$$\Delta R_x = \frac{\sqrt{A_x}}{t}.$$

For the pulse duration τ the error is

$$\Delta\tau = \sqrt{\left(\frac{\partial\tau}{\partial R_{Random}}\Delta R_{Random}\right)^2 + \left(\frac{\partial\tau}{\partial R_A}\Delta R_A\right)^2 + \left(\frac{\partial\tau}{\partial R_B}\Delta R_B\right)^2}.$$

As a result for the measurement in the lab $A_A \approx 16240 \pm 130$, $A_B \approx 15810 \pm 130$ and $A_{Random} = 11 \pm 3$.

Therefore $R_A \approx (4.51 \pm 0.04)\,\frac{1}{\mathrm{s}}$ and $R_B \approx (4.39 \pm 0.04)\,\frac{1}{\mathrm{s}}$.

Finally $R_{Random_l} \approx (0.0031 \pm 0.0009)\,\frac{1}{\mathrm{s}}$ and $\tau_l \approx (80 \pm 20)\,\mathrm{\mu s}$.

This measurement was repeated on the rooftop and in the basement in the same way. On the rooftop $A_{Random_r} = 9$ in the basement $A_{Random_b} = 5$, so $R_{Random_r} \approx (0.0025 \pm 0.0008)\,\frac{1}{\mathrm{s}}$ and $R_{Random_b} \approx (0.0014 \pm 0.0006)\,\frac{1}{\mathrm{s}}$.

With $A_{A_r} = 20883$ and $A_{B_r} = 22688$ for the rooftop τ_r is calculated to $\tau_r \approx (34 \pm 11)\,\mathrm{\mu s}$
With $A_{A_b} = 13237$ and $A_{B_b} = 11504$ for the basement τ_b is calculated to $\tau_b \approx (60 \pm 30)\,\mathrm{\mu s}$

To check the level of significance a t-test n the form of

$$t = \frac{|\hat{x} - \hat{y}|}{\sqrt{(\Delta x)^2 + (\Delta y)^2}}$$

is made.

t-tests between different τ		
lab + roof	lab + basement	roof + basement
2.0	0.6	0.8

Table 1: t-tests

A difference between results is considered significant, when $t \geq 2$. So, because of that the pulse duration is significantly different in the lab compared to the roof, but the τ_b fits as well to the measured τ in the lab and on the rooftop. the very good t values between the basement and the other locations comes from the big uncertainty the value has.

3.3 Zenith angle

The scintillators in the detector plates have the dimension $s = 15\,\text{cm}\cdot 15\,\text{cm}\cdot 1\,\text{cm}$ [Edu21]. Therefore the error is triangular distributed with $a_s = 0.5\,\text{cm}$. With the formula

$$\Delta x = \frac{a_x}{\sqrt{6}}$$

the uncertainty on the dimension is $\Delta s = 0.2\,\text{cm}$ The distance between the scintillators is measured from top to top of the plates. As in the lab book noted the error is estimated very big with $a_d = 0.1\,\text{cm}$ triangularly distributed. This is to big because it means that it is possible to write down the wrong number on the scale. Because we always double checked the measurements an error of $a_d = 0.05\,\text{cm}$ is a much better guess. Therefore we will use half the initial error for all distances. That way the distance is

$$d = (36.50 \pm 0.02)\,\text{cm}.$$

The uncertainty on the zenith angle comes from the triangularly distributed error from reading the scale of $a_\theta = 1°$. Therefore $\Delta\theta = \pm 0.4°$. This error is so big, because the rod was a bit loose to the scale and therefore very hard to read.

The solid angle is defined and calculated for small solid angles by the formula[2]

$$\Omega \approx \frac{ab}{d^2} = \frac{((15.0 \pm 0.2)\,\text{cm})^2}{((36.50 \pm 0.02)\,\text{cm})^2} \approx (0.169 \pm 0.019)\,\text{sr}.$$

All those uncertainties are systematic. Statistical uncertainties come from the Poisson distribution of these measurements. The effect of the zenith angle θ on the muon flux is shown in fig. 3. The color of the dots refer to the amount of shielding. Blue is low, orange medium, and green high shielding, achieved by the different locations.

[2] [Mat22]

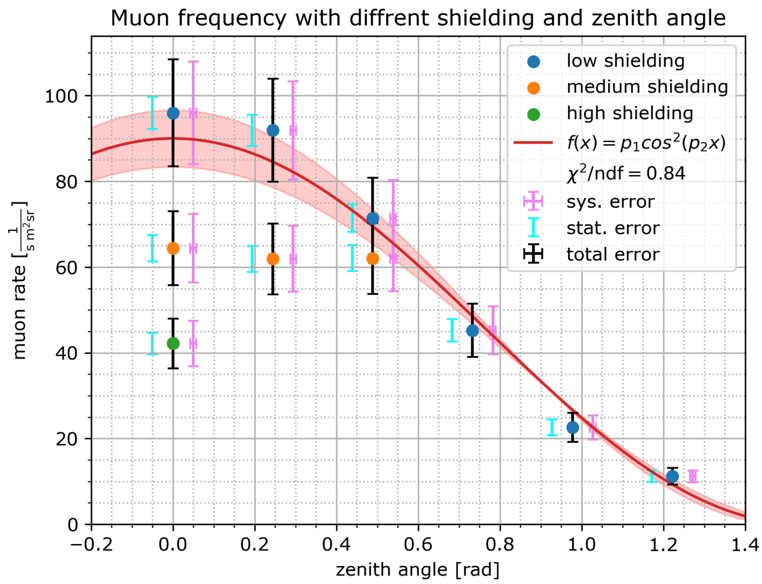


Figure 3: detected muon flux depending on the zenith angle

The detected flux is illustrated in muon rate per square meter per solid angle. The error bars are split in blue statistical errors, pink systematic errors and black combined errors. The fit is made with the function

$$f(x) = p_1 \cos^2(p_2 x)$$

where $p1 = (90.0 \pm 6.6)\,\frac{1}{\mathrm{s\ m^2\ sr}}$ and $p2 = (1.02 \pm 0.02)$, the uncertainty derives from the total error. Only low shielding values were used for the fit to get the best result. The three values with an zenith angle $\theta > 0.5\,\mathrm{rad}$ were made in the lab facing directly a window, the medium shielding values are made in the lab facing the concrete ceiling. Because of the

$$\frac{\chi^2}{ndf} = 0.84,$$

the fit has a great quality and represents the data well.

3.4 Shielding

The vertical measurement is made indoor at the first floor lab, in the basement and outdoor on the high-rise rooftop. With this method the goal is to achieve different levels of shielding to see the effect on the muon flux. The setup is always set to 0°. The Gustav-Mie-Haus has 5 storeys and 2 extra underground storeys. The lab is in the first floor, the basement measurment is in the second floor under ground.

The results are the three values in fig. 3 on the left on top of each other. The blue value is in the lab with medium shielding, the orange one on the roof without shielding and the green one is in the basement with high shielding.

$$R_{blue} = (96 \pm 13)\,\frac{1}{\mathrm{s\ m^2\ sr}},$$

$$R_{orange} = (64 \pm 9)\,\frac{1}{\mathrm{s\ m^2\ sr}},$$

$$R_{green} = (42 \pm 6)\,\frac{1}{\mathrm{s\ m^2\ sr}}.$$

It is obvious from the data, that the shielding of the building has a huge impact. The muon rate of the measurement in the basement is less then half of the rate on the roof with

$$\frac{R_{green}}{R_{blue}} = \frac{R_{basement}}{R_{roof}} = (44 \pm 8)\,\%.$$

3.5 Horizontal measurement

In addition to the standard distance $d = (36.50 \pm 0.02)\,\mathrm{cm}$ three further measurements are taken with the distances $d_1' = (7.90 \pm 0.02)\,\mathrm{cm}$, $d_2' = (17.30 \pm 0.02)\,\mathrm{cm}$ and $d_3' = (25.10 \pm 0.02)\,\mathrm{cm}$. It is important to note that in fig. 4 the muon rate is not normalized on the solid angle.

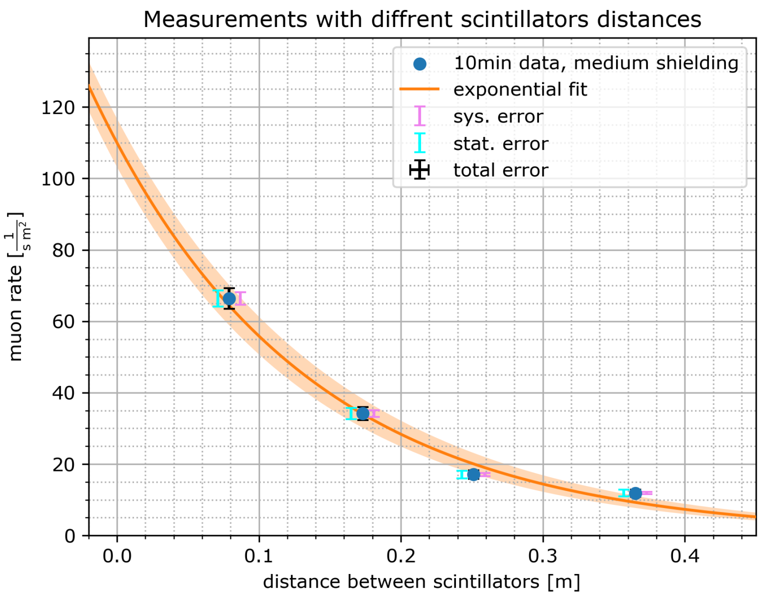


Figure 4: muon rate as a function of scintillator distance

These measurements were then fitted with a exponential fit in the form of

$$R(d) = R_0 \exp(-\lambda d).$$

It does not fit particularly good with reduced $\chi^2 = 7.8$, but a better fit, would have required more data points. The interesting point is the offset from 0 at $d = 0$ of the fit. It is given as

$$R_{horizontal} = (110 \pm 7)\,\frac{1}{\text{s m}^2}$$

and is an estimation of the total muon rate of the hemisphere. It can also be obtained by integrating over the Zenith angle $\cos^2$-plot, via:

$$R_{horizontal} = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} p_1 \cos{(p_2\theta)}^2 \sin{(\theta)}\, d\theta\, d\phi = \frac{2\pi}{3} p_0 = (189 \pm 14)\,\frac{1}{\text{s m}^2}.$$

Those two results are significantly different.

4 Discussion

4.1 Final results

The muon flux is Poisson distributed.

The pulse duration is calculated in the lab, on the rooftop and in the basement to

$$\tau_l \approx (80 \pm 20)\,\mu\text{s},$$

$$\tau_r \approx (34 \pm 11)\,\mu\text{s},$$

$$\tau_b \approx (60 \pm 30)\,\mu\text{s}.$$

The muon flux depending on the zenith angle θ behaves like the function

$$f(x) = p_1 \cos^2{(p_2 x)}.$$

For an Angle of $\theta = 0°$ the muon flux has a rate of

$$R_{\theta=0°} = (96 \pm 13)\,\frac{1}{\text{s m}^2\text{ sr}}.$$

The effect of shielding reduced the detected muon rate about

$$\frac{R_{basement}}{R_{roof}} = (44 \pm 8)\,\%.$$

With two scintillators positioned horizontally and directly on top of each other, the muon rate is calculated to

$$R_{horizontal} = (110 \pm 7)\,\frac{1}{\text{s m}^2}$$

via measurements with different scintillator distances or

$$R_{horizontal} = (189 \pm 14)\,\frac{1}{\text{s m}^2}$$

via the integration over the zenith angle fit.

4.2 Comparison with expected results

4.2.1 Probability Distribution of muon flux

It is expected to have a Poisson distribution because the amount of measurements n is high and the success is small. So the measurements confirms the prediction.

4.2.2 Random Coincidence

According to the manual[3] the pulse duration should be $\tau = 700\,\mathrm{ns}$. The here taken measurements do not confirm this. The measurements suggest a greater pulse duration. Alternatively the coincidences could be triggered by a cosmic shower which widens so much, that it triggers the scintillators at the same time, even if they are far apart. In any case the random coincidence rate can not be predicted accurately with a pulse duration of $\tau = 700\,\mathrm{ns}$ and the formula given by the manual $R_{Random} = 2R_A R_B \tau$ [Edu21].

4.2.3 Zenith angle

It is clear, that the muon flux is dependent on the zenith angle and it can be described nicely by a function of $f(x) = p_1 cos(p_2 x)^2$ where x is the zenith angle in radians. This is reasonable, because the travel distance and time through the atmosphere to the detector increases with increasing zenith angles. This effectively blocks the low energy muons from reaching the angled detector setup, so the only detected muons are those with a high energy. So fewer than with a smaller zenith angle. This is not compensated by the in theory bigger origin area from which the muons are detected. For an angle $\theta = 0°$ the detected rate is $R_{p_1} = (90.0 \pm 6.6)\,\frac{1}{\mathrm{s\ m^2\ sr}}$. this is very similar compared to the value in fig. 6 with an Vertical flux at sea level of $R \approx 90\,\frac{1}{\mathrm{s\ m^2\ sr}}$.

4.2.4 Shielding

It is expected that the Shielding has a big effect on the muon flux.

t-tests	
roof → lab	lab → basement
2.024	2.034

Table 2: t-tests between different locations

With the t-tests it is possible to see, that the values between lab and basement are further apart from each other then the values between roof and lab. So according to this the shielding of muons is not linear. On the other hand this is hard to tell, because there is one concrete ceiling more between the sky and the lab, but the ceilings of the ground floor is much bigger then the other ones, which is visible in fig. 7 in the attachments.

[3] [Edu21]

4.2.5 Horizontal Measurements

The two different methods for estimating the muon intensity from the whole upper hemisphere yield significantly different results. This is not as disappointing as it may seem because the measurements were taken in the building for the varying distance measurement, and taken outside for the zenith angle measurements. This could explain the difference but needs some further research.

5 Attachment

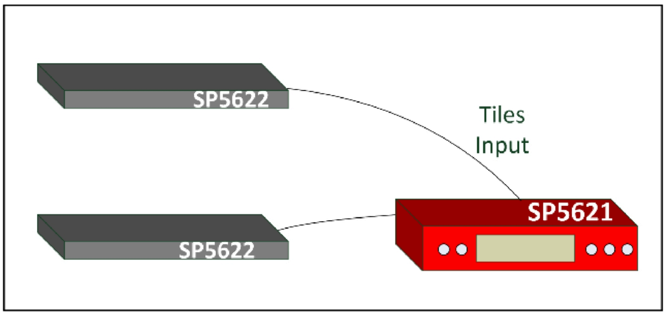


Figure 5: Setup for the random coincidence measurement

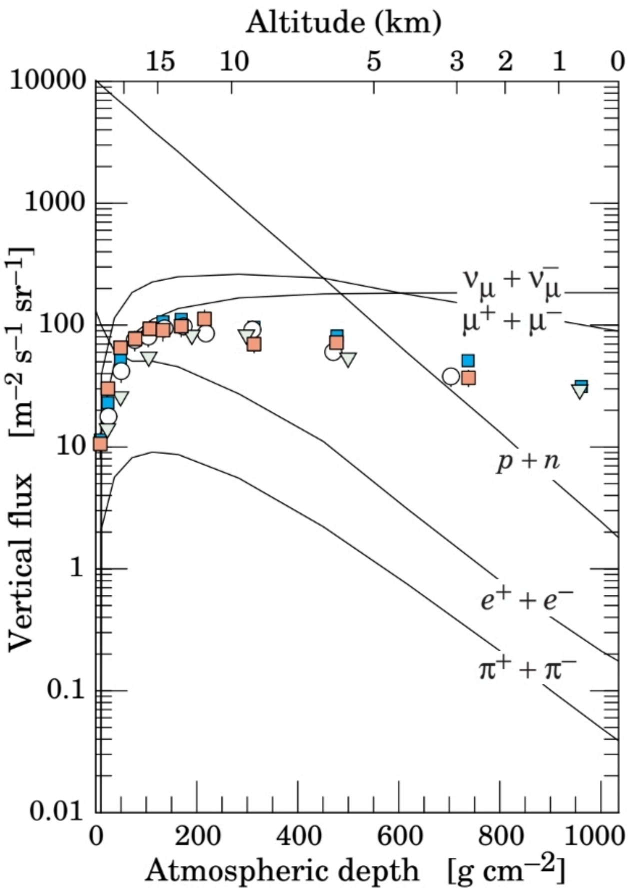


Figure 6: "Vertical fluxes of cosmic rays in the atmosphere with $E > 1\,\mathrm{Gev}$" [JJ 18]

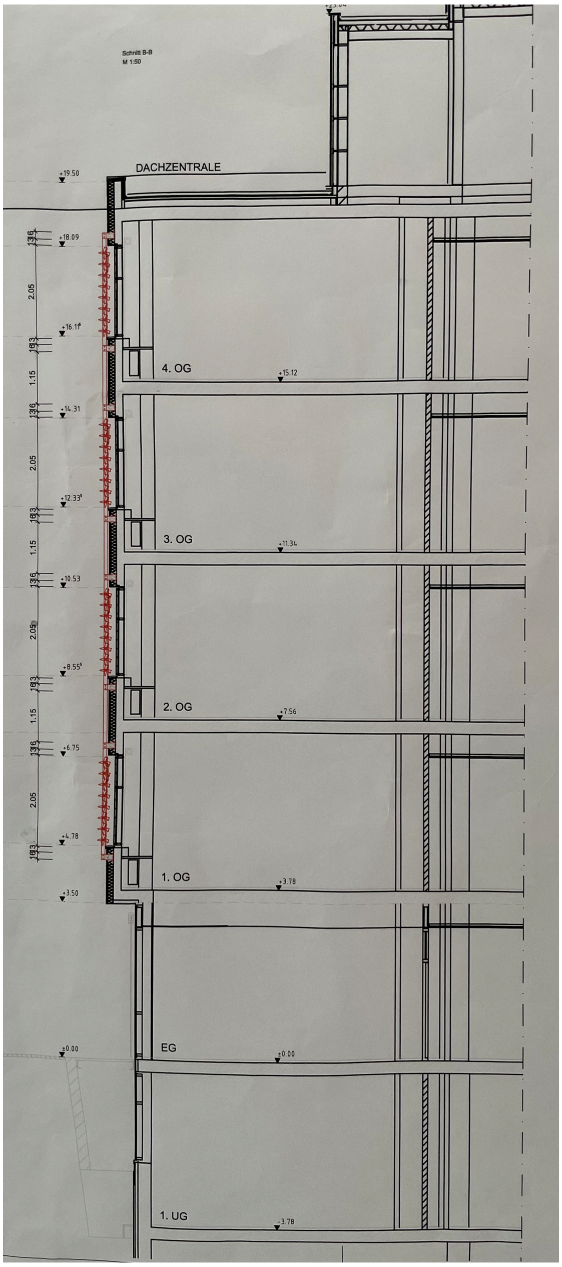
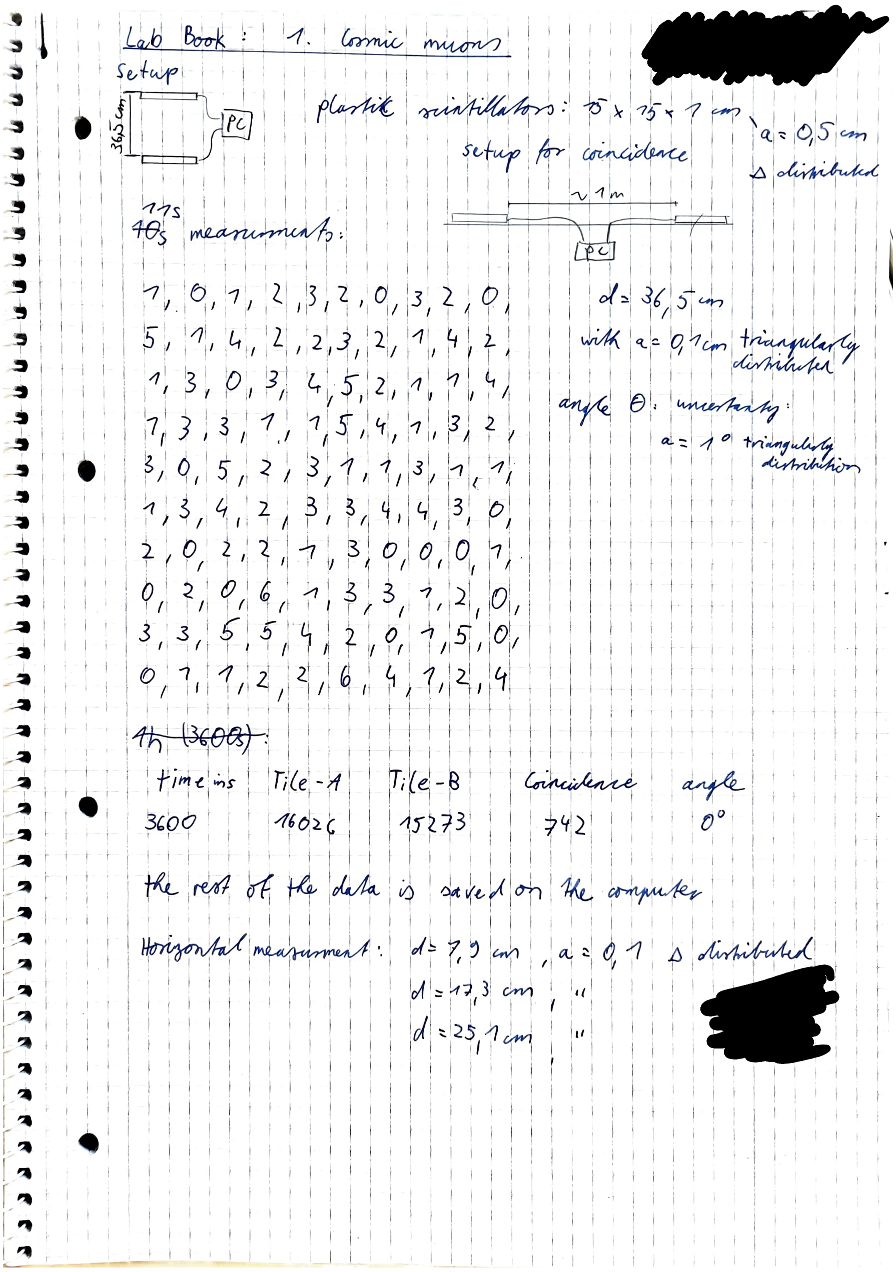


Figure 7: Construction plan of Gustav-Mie-Haus[Wei24]

5.1 Lab book



Lab Book : 1. Cosmic muons [redacted]

Setup

36,5 cm

PC

plastik scintillators: 15 x 15 x 1 cm, a = 0,5 cm

setup for coincidence

Δ distributed

~1m

PC

~~10s~~ 11s measurements:

1, 0, 1, 2, 3, 2, 0, 3, 2, 0,
5, 1, 4, 2, 2, 3, 2, 1, 4, 2,
1, 3, 0, 3, 4, 5, 2, 1, 1, 4,
1, 3, 3, 1, 1, 5, 4, 1, 3, 2,
3, 0, 5, 2, 3, 1, 1, 3, 1, 1,
1, 3, 4, 2, 3, 3, 4, 4, 3, 0,
2, 0, 2, 2, 1, 3, 0, 0, 0, 1,
0, 2, 0, 6, 1, 3, 3, 1, 2, 0,
3, 3, 5, 5, 4, 2, 0, 1, 5, 0,
0, 1, 1, 2, 2, 6, 4, 1, 2, 4

d = 36,5 cm

with a = 0,1 cm triangularly distributed

angle θ: uncertainty:

a = 1° triangularly distribution

~~1h (3600s)~~:

time in s	Tile-A	Tile-B	Coincidence	angle
3600	16026	15273	742	0°

the rest of the data is saved on the computer

Horizontal measurement: d = 7,9 cm , a = 0,1 Δ distributed
d = 17,3 cm , "
d = 25,1 cm , "

[redacted]

Figure 8: Rohdaten

literature

[Edu21] CAEN Educational. *Quickstart Guide Cosmic Hunter*. Mar. 16, 2021. URL: https://ilias.uni-freiburg.de/goto.php?target=file_3555604_download&client_id=unifreiburg (visited on 08/21/2024).

[JJ 18] S.P. Wakely J.J. Beatty J. Matthews. *29. Cosmic Rays*. June 5, 2018. URL: https://ilias.uni-freiburg.de/goto.php?target=file_3555606_download&client_id=unifreiburg (visited on 08/21/2024).

[Mat22] Richard J. Mathar. *Solid Angle of a Rectangular Plate*. Jan. 28, 2022. URL: https://ilias.uni-freiburg.de/goto.php?target=file_3558530_download&client_id=unifreiburg (visited on 08/21/2024).

[Wei] Christian Weiser. *Kosmische Myonen*. URL: https://ilias.uni-freiburg.de/goto.php?target=fold_3555554&client_id=unifreiburg (visited on 08/27/2024).

[Wei24] Christian Weiser. *Map Building 2*. Aug. 13, 2024. URL: https://ilias.uni-freiburg.de/goto.php?target=file_3572085&client_id=unifreiburg (visited on 08/21/2024).