Measurement of the Asymmetry of the Cosmic Ray Muon Flux: Background Context

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Contents

1 Sources of Ionising Radiation

Aside from muons, there are different sources of ionising radiation that are capable of triggering the Desktop Muon Detector (This is the detector that was developped during the thesis project.

1.1 Cosmic Radiation

We can understand cosmic rays are a flux of particles:

- 74% Ionized hydrogen
- 18% Helium nuclei
- Trace amounts of heavier elements

The majority of the cosmic ray flux observed from Earth is relativistic. In this context, we understand "relativistic" to mean individual nuclei having kinetic energy greater than their rest mass energy. Thus,

$$\frac{E_k}{mc^2} > 1$$

Lower-energy cosmic rays (at the GeV scale) are greatly influenced by solar winds as well as the geomagnetic field, which limits their flux interacting with the Earth.

The high-energy flux extends up to 10^{11} GeV, at which point cosmic rays lose energy due to interactions with the cosmic microwave background—a phenomenon known as the GZK cutoff.

When a primary cosmic ray collides with a nucleus in the upper atmosphere (usually an oxygen or nitrogen nucleus), the energy is high enough to break apart both the primary particle and the target nucleus through nuclear interactions. Most of the collision energy goes into producing short-lived particles called mesons. You can find more information about mesons in appendix A

Charged mesons travel enough before decaying to interact with other molecules in the atmosphere. This causes a shower of particles induced by primary interactions.

1.1.1 Primary Cosmic Ray Interaction

High energy proton (cosmic ray) hits a nucleus in the atmosphere.

$$p + \text{Nucleus} \rightarrow \text{Hadrons} + \pi^{\pm,0} + K^{\pm,0} + \cdots$$

This will later lead to the subsequent decay of both pions and mesons.A

Muons are a byproduct of the mesons decay, they usually decay at low altitudes:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

Later muons decay further B

The atmosphere protects us from primary cosmic rays, but a small flux of nuclear fragments (protons and neutrons make it to the surface.

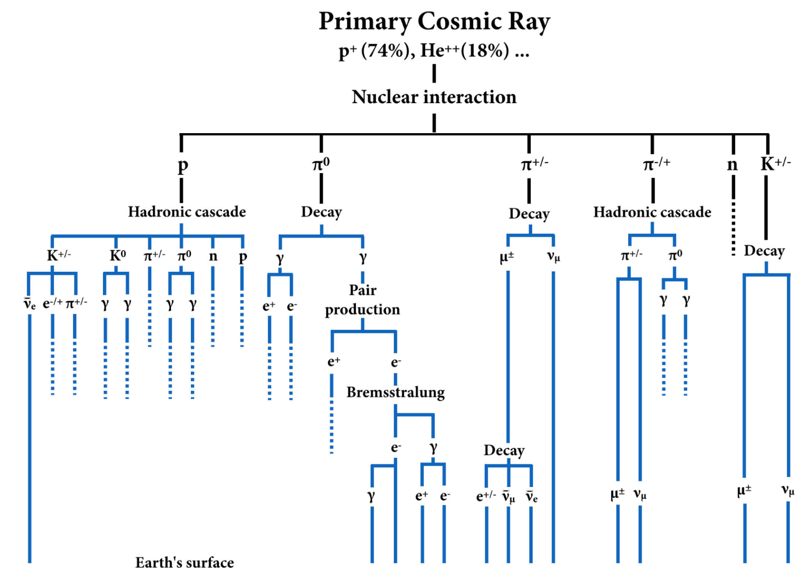

Figure 1: An schematic representation of the various decay and interactions chains that result from the interaction of a cosmic-ray in Earth's atmosphere. Image extracted from: [1]

1.2 Number and type of Particles at Sea Level

In this section, the number of particles shown comes from one steradian about the zenith, or one sixth of the visible sky (32°). Taking this in account the number of particles at sea level is:

Table 1: Approximate particle fluxes at sea level from one steradian about the zenith.

Particle Type	**Energy Threshold**	**Flux (cm^{-2} min^{-1} sr^{-1})**
Muons ($\mu^{\pm}$)	> 1 GeV	0.4
Electrons/positrons ($e^{\pm}$)	> 10 MeV	0.2
Protons	> 1 GeV	0.0054
Charged mesons (e.g., $\pi^{\pm}$, $K^{\pm}$)	> 1 GeV	$\sim 5 \times 10^{-5}$

2 Flux Variation due to External Factors

The intensity of the muon flux is affected by several factors in space:

- The Sun's magnetic field / Solar activity
- Earth's magnetic field

2.1 Latitude Effect

The Earth's magnetic field acts like a shield. This shield is non-homogeneous:

- Near the equator: it deflects a higher percentage of cosmic rays
- Near the poles: less deflection, a higher percentage of the cosmic rays reach Earth's ground.

We can study the Earth's magnetic field as a magnetic dipole, where the magnetic field lines are horizontal near the Equator and vertical at the poles. This affects the path of the particles.

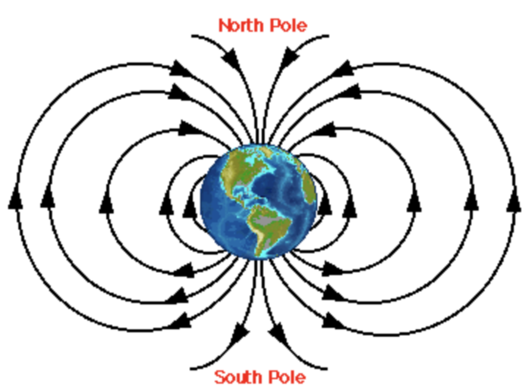

Figure 2: The Earth's magnetic field resembles that of an enormous bar magnet. The field lines emerge from the southern half of the earth and re-enter in the northern half. Image extracted from: [2]

2.1.1 Lorentz Force

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

A charged particle experiences a force when it moves through a magnetic field. This force depends on the angle between the particle's velocity and the magnetic field.

Near the equator, the Earth's magnetic field is predominantly horizontal (i.e., perpendicular to the radial direction of incoming cosmic rays), so the cross product $\vec{v} \times \vec{B}$ is larger. This results in stronger deflection of incoming charged particles.

Conversely, near the poles, the magnetic field is more vertical and roughly aligned with the direction of incoming particles, so $\vec{v} \times \vec{B}$ is smaller. As a result, charged particles experience less deflection.

In summary, this means that the higher the latitude, the more easily charged particles can penetrate the Earth's magnetic field and reach the ground.

2.1.2 Rigidity and Energy Cutoff

The Earth's magnetic field acts as a natural shield against low-energy charged particles. This shielding depends on the particle's rigidity, defined as momentum per unit charge, and given by

$$R = \frac{pc}{q},$$

where p is the particle's momentum, c is the speed of light, and q is its electric charge.

Only particles with rigidities above a certain cutoff can penetrate the magnetic field and reach the atmosphere. This cutoff rigidity varies with geomagnetic latitude due to the shape and orientation of the Earth's magnetic field. Near the equator, where the field lines are more horizontal, the cutoff is highest—typically around 10 GV. Near the poles, where the field lines are more vertical, the cutoff drops to about 1 GV.

This means that lower-energy cosmic rays are more likely to reach the Earth's surface near the poles, while equatorial regions are better shielded. This variation in geomagnetic shielding also explains why polar regions have higher cosmic ray flux at ground level.

2.2 East-West Asymmetry

The east-west asymmetry is a consequence of the Earth's magnetic field. More muons are observed arriving from the west than from the east.

Charged particles moving through a magnetic field experience a Lorentz force:

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

This force causes their paths to curve, with the direction of curvature depending on the particle's charge and its velocity. At low latitudes (near the equator), the Earth's magnetic field is predominantly horizontal and points roughly northward.

This configuration leads to an observable east-west asymmetry:

- **Positively charged particles**: As they enter Earth's magnetic field, they are deflected **eastward**, so we detect them coming predominantly from the **west**.
- **Negatively charged particles**: These are deflected **westward**, so we detect them coming predominantly from the **east**.

This deflection is strongest at the equator and becomes negligible near the poles. The observed asymmetry is primarily due to the fact that most primary cosmic rays are positively charged.

2.2.1 Muon Deflection in Our Experiment

- **Positive muons (μ^+)**
  - Tend to arrive from the *west*
  - Originate from decays of positively charged cosmic ray secondaries (e.g., π^+)
  - Deflected *eastward* by Earth's magnetic field
- **Negative muons (μ^-)**
  - Tend to arrive from the *east*
  - Originate from decays of negatively charged cosmic ray secondaries (e.g., π^-)
  - Deflected *westward* by Earth's magnetic field

The muon flux observed at Earth's surface is larger when looking toward the west compared to the east. This east-west asymmetry is a consequence of the Earth's magnetic field acting on charged particles. Since most primary cosmic rays are positively charged (mainly protons), their secondaries, such as positive pions, decay into positive muons, which are deflected eastward. As a result, more muons appear to arrive from the west.

This effect is more pronounced in the upper atmosphere, where deflection occurs, and is stronger at lower geomagnetic latitudes (e.g., near the equator) where the magnetic field is more horizontal. Near the poles, the field is more vertical, and the asymmetry becomes negligible.

2.3 Flux Variations due to Atmospheric Properties

2.3.1 The Cosine Squared Law

Cosmic ray muons arriving at larger zenith angles must traverse longer paths through the atmosphere. The greater this path length, the higher the energy losses due to ionization and the greater the probability that the particles will decay before reaching the ground.

As a result, the number of muons detected at the Earth's surface decreases with increasing zenith angle. This dependence can be approximated by a cosine-squared function:

$$I(\theta) \propto \cos^2 \theta$$

where θ is the zenith angle, measured from the vertical.

Muons arriving from near-vertical directions ($\theta \approx 0^\circ$) are more likely to reach the ground than those arriving from near-horizontal directions ($\theta \approx 90^\circ$). This is because the atmosphere is approximately 15 km thick vertically, but the effective path through the atmosphere increases significantly with angle—reaching up to hundreds of kilometers near the horizon.

Thus, the flux of cosmic muons is highest at small zenith angles and falls off sharply as the angle increases.

2.3.2 Atmospheric Attenuation

Atmospheric attenuation refers to the reduction in the intensity of cosmic ray particles as they pass through the Earth's atmosphere. The thicker the atmosphere, the fewer particles, particularly electrons and low-energy secondary particles, are able to reach the ground.

Before reaching sea level, the following chain of interactions occurs:

- Primary cosmic rays (mainly protons) arrive from outer space and collide with nuclei in the upper atmosphere.
- These collisions produce showers of secondary particles: muons, pions, electrons, neutrinos, and others.
- Muons are relatively long-lived and highly penetrating, making them the most likely of these secondaries to reach sea level.

Atmospheric pressure and muon detection rate are anticorrelated: as atmospheric pressure increases, the rate of muon detection decreases. This is because a denser atmosphere increases the likelihood of muon decay or absorption before they can reach the detector. Therefore, detectors must account for the barometric effect when analyzing muon flux.

Atmospheric density also varies with seasons, introducing a time-dependent variation in muon flux:

- **Summer**: The atmosphere heats up and expands, lowering its density at a given altitude. Muons are typically produced higher up, increasing the chance of decay before reaching sea level. This results in a lower muon rate.
- **Winter**: The atmosphere cools and contracts, becoming denser at lower altitudes. Muons are produced closer to the surface, increasing their chances of being detected. This results in a higher muon rate.

This seasonal variation in atmospheric conditions leads to a change in the muon flux of approximately 1–3%.

2.3.3 Temperature Effect

Temperature changes in the atmosphere can have both positive and negative effects on the muon flux observed at the Earth's surface.

- **Positive Temperature Effect:**
  As the temperature increases, the upper atmosphere expands and its density decreases. With fewer air molecules to interact with, mesons (such as pions and kaons) produced in cosmic ray collisions are more likely to decay into muons rather than interact with other particles. This leads to an increased production of muons—especially high-energy ones.
- **Negative Temperature Effect:**
  Higher temperatures cause the production of secondary particles to occur at higher altitudes. As a result, muons must travel a longer distance to reach detectors at the surface. Low-energy muons are more likely to decay before reaching the ground, leading to a reduction in their observed flux.
- **Overall Consequence of Temperature:**
  - At **low energies** (and near sea level), the negative effect dominates. Thus, higher atmospheric temperatures result in fewer detectable muons.
  - At **high energies** (especially in underground detectors), the positive effect dominates. In this case, higher temperatures can result in an increased muon flux.

3 Radioactive Background

The detectors are also sensitive to ionising radiation originating from radioactive materials on or near the Earth's surface, which can influence our measurements.

There are three main types of radioactive decay processes that contribute to this background: alpha (α), beta (β), and gamma (γ) radiation.

The energy scale of these processes is typically in the MeV range, which is significantly lower than the GeV energies associated with cosmic rays. However, because radioactive decays occur much more frequently, they can dominate the overall rate of detected events at ground level—especially in environments shielded from cosmic rays. You can read more about the subject in Appendix C

4 Particle Interactions with Matter

To detect a particle, it must interact with the detector by depositing energy within it.

4.1 High-Energy Heavy Charged Particles

This discussion applies to charged particles with mass $m \gg m_e$ (i.e., all charged particles except electrons and positrons).

We study the *stopping power*, defined as the energy loss per unit distance:

$$-\frac{dE}{dx}$$

for a charged particle moving through a medium. The stopping power is usually expressed in units of $\mathrm{MeV\,cm^2/g}$, which, when multiplied by the density of the material $\mathrm{g/cm^3}$, gives the energy loss per unit length MeV/cm.

Particles lose energy in matter primarily through:

- Ionization: removing electrons from atoms (creating ions)
- Excitation: raising electrons to higher energy states without ionizing them

As a particle travels through matter, its energy loss behavior can be divided into three regions, depending on the particle's kinetic energy and mass:

- **Sub-relativistic Region** ($E_k < mc^2$):
  - The particle moves relatively slowly; energy loss increases as it slows down due to increased interaction time with atoms.
- **Ionization Region** ($E_k > mc^2$):
  - Ionization dominates energy loss. Most cosmic ray muons observed at sea level fall into this category.
  - The energy loss is relatively constant over a wide energy range, known as the minimum ionizing region.
- **Radiation Region** ($E > 400\,\mathrm{GeV}$):
  - At extremely high energies, radiative processes such as Bremsstrahlung, pair production, and photonuclear interactions dominate.
  - This region is not relevant for most particles detected at sea level.

5 Scintillators

Scintillators are materials that absorb energy from ionizing radiation (primarily through Coulomb interactions) and reemit it in the form of electromagnetic radiation, typically visible or ultraviolet light. This reemitted light is known as scintillation. There are different types of scintillators, including organic and inorganic materials, depending on the application and energy range.

5.1 How do they work?

1. A high-energy particle (such as a muon, electron, or α particle) passes through the scintillator.
2. It interacts electromagnetically with the electrons in the material via Coulomb interactions.
3. These interactions excite the atoms or molecules of the scintillator, causing them to absorb energy and move to a higher energy state.
4. When the excited atoms or molecules return to their ground state, they release the excess energy as photons (scintillation light).

5.2 Types of Scintillators

- **Inorganic Scintillators**
  - Typically made from doped crystals, where specific atoms (activators) are added to enhance light emission.
  - High density, making them more likely to interact with ionizing radiation.
  - High light yield, producing many photons per unit of deposited energy.
  - Generally more expensive and have slower response times compared to organic scintillators.
- **Organic Scintillators**
  - Based on carbon-containing (organic) molecules.
  - Available in various forms:
    * **Plastic**: Polystyrene or acrylic base mixed with a fluorescent additive.
    * **Liquid**: Solvents like toluene or mineral oil with dissolved fluors.
    * **Gaseous**: Less common, but used in some specialized detectors.
  - Relatively cheap, easy to manufacture, and have fast response times.
  - Lower density and lower light yield than inorganic scintillators.

5.3 Steps in the Detector

A Mesons

Mesons are hadronic particles composed of one quark and one antiquark, bound together by the strong interaction. They are generally unstable and decay into lighter particles through various decay channels. They usually decay within a billionth of a second.

Some common mesons include the pion (π) and kaon (K) families.

A.1 Pion Decay

The charged pions π^+ and π^- primarily decay via weak interactions:

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

The neutral pion π^0 decays electromagnetically, mainly into two photons:

$$\pi^0 \to \gamma + \gamma$$

A.2 Kaon Decay

Charged kaons have several decay modes; one common decay is:

$$K^+ \to \mu^+ + \nu_\mu$$

Neutral kaons exhibit more complex behavior, including mixing and CP violation, but a typical decay is:

$$K_L^0 \to \pi^\pm + e^\mp + \nu_e$$

B Muons and Muon Decay

Muons ($\mu^\pm$) are charged leptons similar to electrons but with a mass approximately 200 times greater. They do not participate in the strong interaction, but they are unstable and decay via the weak interaction.

B.1 Muon Properties

- Mass: $m_\mu \approx 105.7\,\mathrm{MeV}/c^2$
- Lifetime: $\tau \approx 2.2 \times 10^{-6}\,\mathrm{s}$
- Charge: μ^+ (positive), μ^- (negative)

B.2 Muon Decay

The most common decay of the muon is a three-body process mediated by the weak force:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

This process is mediated by a **virtual $W^\pm$ boson**, which is the carrier of the charged weak interaction. The W boson is not directly observed in the decay because it exists only transiently (virtually) and is off-shell.

B.3 Role in Particle Showers

Muons are frequently produced in **cosmic ray showers** from the decay of pions and kaons. Due to their relatively long lifetime and penetrating power, muons often reach the Earth's surface and are commonly detected in cosmic ray experiments.

C Types of Radioactive Decay

Radioactive decay refers to the spontaneous transformation of an unstable atomic nucleus into a more stable one. The main types of radioactive decay relevant to ionising radiation detection are:

Alpha Decay (α-decay)

Alpha decay occurs when an unstable nucleus emits an alpha particle, which consists of two protons and two neutrons (a helium nucleus). This results in a new element with a mass number reduced by 4 and atomic number reduced by 2:

$$^{A}_{Z}\mathrm{X} \rightarrow ^{A-4}_{Z-2}\mathrm{Y} + ^{4}_{2}\mathrm{He}$$

Beta-minus Decay (β^--decay)

In beta-minus decay, a neutron inside the nucleus is converted into a proton, with the emission of an electron (β^-) and an antineutrino ($\bar{\nu}_e$):

$$^{A}_{Z}\mathrm{X} \rightarrow ^{A}_{Z+1}\mathrm{Y} + \beta^- + \bar{\nu}_e$$

Beta-plus Decay (β^+-decay)

In beta-plus decay, a proton is converted into a neutron, emitting a positron (β^+) and a neutrino (ν_e):

$$^{A}_{Z}\mathrm{X} \rightarrow ^{A}_{Z-1}\mathrm{Y} + \beta^+ + \nu_e$$

Gamma Decay (γ-decay)

Gamma decay involves the emission of a high-energy photon when a nucleus transitions from an excited state to a lower energy state. The atomic and mass numbers remain unchanged:

$$^{A}_{Z}\mathrm{X}^* \rightarrow ^{A}_{Z}\mathrm{X} + \gamma$$

These processes form the basis of the radioactive background that can influence measurements with ionisation detectors like the Desktop Muon Detector.

[**label**]

References

[1] Spencer N. Axani. *The Physics Behind the CosmicWatch Desktop Muon Detectors*. 2019. arXiv: `1908.00146 [physics.ins-det]`. URL: `https://arxiv.org/abs/1908.00146`.

[2] *The Earth's Magnetic Field — oceanweb.sites.oasis.unc.edu*. `https://oceanweb.sites.oasis.unc.edu/www.unc.edu/depts/oceanweb/turtles/geomag.html`. [Accessed 09-06-2025].