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MUONS AND THE STANDARD MODEL OF PARTICLE PHYSICS

The muon is one of the elementary particles, meaning it is not made up of smaller, more fundamental components. Elementary particles are divided into two main categories: "quarks" and "leptons." There are six types of quarks—up, down, charm, strange, top, and bottom—and six types of leptons: the electron, muon, tau, and their corresponding neutrinos. Additionally, there are mediator particles that facilitate the fundamental forces, including the photon (which mediates the electromagnetic force), gluons (which mediate the strong force), and the W^+, W^- and Z^0 bosons (which mediate the weak force). The Higgs boson, another elementary particle, is responsible for giving mass to other elementary particles (see Figure 1).

Named after the Greek letter "mu," the muon behaves similarly to the electron but has a mass approximately 200 times greater. This increased mass makes the muon highly unstable, with a very short lifetime of about 2 millionths of a second. During its decay, a muon transforms into an electron, a neutrino, and an antineutrino. Due to their rapid decay, muons are typically observed in high-energy particle accelerators or as secondary particles generated by cosmic rays.

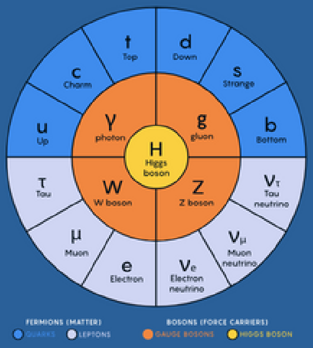

FIGURE1. STANDARD MODEL OF PARTÍCULES PHYSICS AND PARTICLES CARRYING THE FORCES

Muons are notably more penetrating than electrons or photons. High-energy muons can travel hundreds of meters through rock before coming to a stop.

Muons are produced in large numbers when cosmic rays collide with the upper atmosphere of Earth. These particles reach the Earth's surface and even penetrate deep into the planet. The flux of muons at sea level is significant, with more than 100 muons per square meter per second.

The high energies of atmospheric muons, coupled with their speeds approaching the speed of light, allow them to be detected on Earth before they decay. According to the theory of relativity, time passes more slowly for a moving muon. For example, a muon with an energy of 2 GeV (2 billion electron volts) has a lifetime of 2.2 microseconds in its own frame of reference, but in the frame of reference of an Earth observer, this corresponds to a lifetime of 42 microseconds. In terms of distance, a muon traveling 660 meters in its own frame of reference would appear to travel 13 kilometers from the perspective of an Earth observer.

Muons play a crucial role in studying secondary particle cascades, or extended atmospheric showers, which are of great interest to the Pierre Auger Observatory. The number of muons in these showers is related to the composition of the primary cosmic ray, with heavier nuclei producing more muons. By measuring the muon content of atmospheric showers, using methods such as scintillation detectors (see Auger in Focus #3, July 2024, and #5, September 2024), we can gain insight into the nature of cosmic rays and the particles they consist of.

Until recently, the study of muons was primarily focused on understanding their properties and origins as a form of natural radiation we encounter daily. However, they are currently also used in unique studies that allow for X-rays of pyramids or volcanoes and the analysis of facilities that are not accessible. One such technique, "muon tomography," enables the determination of the internal density distribution of massive objects (see Figure 2).

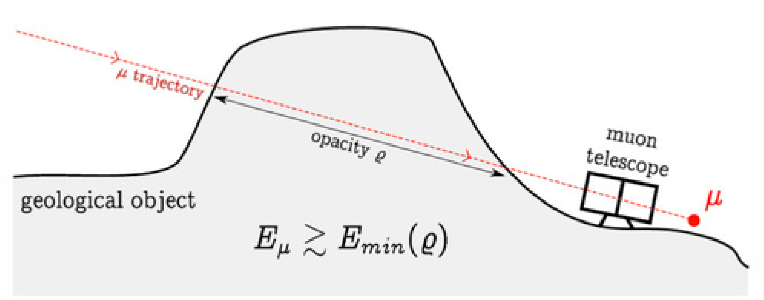

FIGURE 2. SCHEMATIC OF A MUON TOMOGRAPHY SETUP FOR DETERMINING THE INTERNAL DENSITY OF A GEOLOGICAL STRUCTURE. OPACITY IS THE AMOUNT OF MATTER ALONG THE MUON PATH, WHICH IS CONSIDERED A STRAIGHT LINE.

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