

PROBING FUNDAMENTAL PARTICLE INTERACTIONS WITH THE PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory is the world's largest observatory of ultra-high-energy cosmic rays (UHECRs). These can be protons (the positively charged particles found in atomic nuclei) or heavier nuclei, accelerated in extreme environments across our Universe. After travelling through intergalactic space, they collide with Earth's atmosphere, depositing tremendous amounts of energy. A single proton with an energy of 10^{20} eV carries as much energy as our bodies obtain from a grain of sugar. Yet, if the trillions of protons and neutrons in that grain carried as much energy as this cosmic ray, together they could power our civilization for more than 10 years!

When a cosmic ray collides with the atmosphere, it produces thousands of new particles, which interact again and again, creating a cascade known as an Extensive Air Shower [see Fig. 1]. Some of the energy is carried by so-called hadrons and, over many steps of the cascade, gives rise to muons (heavier cousins of electrons). The rest of the energy is given to electrons (the same particles that move through the electric wires powering our houses), positrons (the opposite of electrons), and photons (the particles of light). At first, the shower grows as energetic particles produce more particles. Eventually, they lose enough energy that their number begins to decrease. The atmospheric depth where the shower reaches its maximum size is called $X_{\max}$.

The Pierre Auger Observatory measures $X_{\max}$ with great precision. Importantly, the value of $X_{\max}$ is very sensitive to how these high-energy collisions work. This is crucial because we do not have a theory that can uniquely predict these interactions, nor data to probe them using human-made accelerators at such extreme energies. But Auger can probe them. So, what did we do?

1. We used different descriptions of high-energy collisions—the so-called hadronic interaction models—to simulate air showers and compare them with Auger data. None of the models could simultaneously reproduce all observations. Matching the data requires showers to have much larger values of $X_{\max}$ and produce about 20% more muons.
2. We then asked: how much should the first collision (the first step of the cascade) change to produce both a larger value of $X_{\max}$ and more muons? Now, the changes in this interaction affect how the cosmic-ray energy is distributed among the produced particles. Different ways of distributing this energy give rise to different values of what we call multiparticle production quantities. One quantity is the fraction of energy given to hadrons α_{had} (alpha). Another quantity is ζ (zeta), and it measures how asymmetrically the cosmic-ray energy is distributed (that is, whether all produced particles have similar energies or whether a few are much more energetic than the others). These variables are closely connected to $X_{\max}$, allowing us to turn the problem around: given the $X_{\max}$ measured by Auger, what values must they have? In Fig. 2, solid markers represent the model predictions, while empty markers show the values preferred by the Auger data. The black lines are the extrapolations we use to “turn the problem around” and estimate the values of the production quantities.

Interpreting these quantities can be complicated, but α_{had} has a particularly intuitive meaning: the larger it is, the more muons we expect. So, the same changes predicted by the larger $X_{\max}$ values also lead to more muons, just like the Auger data prefer!

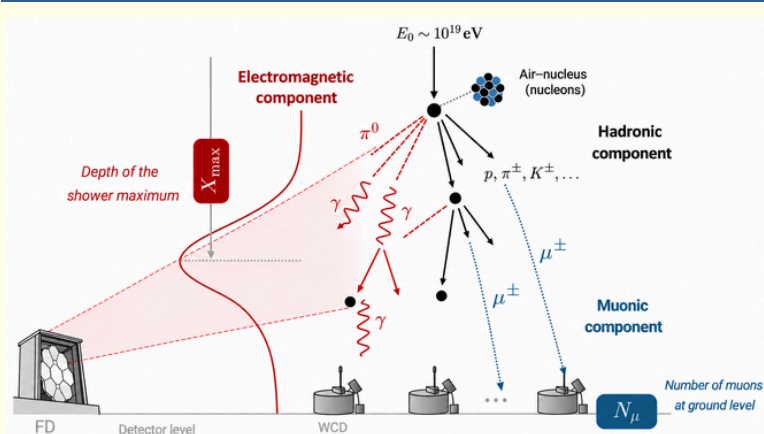


Fig. 1 Scheme of an extensive air shower started by an ultra-high-energy cosmic ray. Particles that tend to decay into muons are shown in black. Muons are in blue, while particles of the electromagnetic component are in red. The Fluorescence Detector (FD) measures $X_{\max}$ and the Water-Cherenkov Detector (WCD) measures the particle content of the shower at ground.

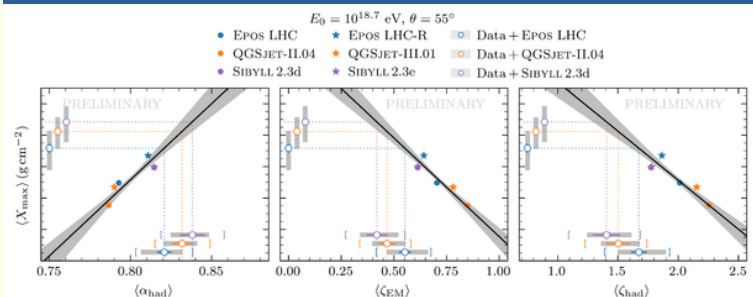


Fig. 2 The average value of $X_{\max}$ against the average value of multiparticle production quantities of the cosmic-ray-air interaction. The full markers represent model predictions. The black line extrapolates the trend followed by the models. The empty markers close to the vertical axis indicate the values of $X_{\max}$ preferred by Auger data, while the empty markers close to the horizontal axis are the corresponding production variables.

In conclusion, we found a way to change the first collision that helps explain both the $X_{\max}$ discrepancy and the long-standing shortage of muons in simulations: the infamous muon puzzle. These results have recently been submitted for publication. They show how Auger can use the most energetic particles in the Universe to study fundamental particle interactions at energies beyond the reach of human-made accelerators.