Astroparticle physics is the field dedicated to understanding how and why the Universe is as it is. Using the theories and models understood and tested in particle physics laboratories, it observes the Universe and the astrophysical sources with different eyes: the particles, also called "the messengers." The most abundant and easy-to-detect messenger is the gamma rays: almost every source produces them as energy emission; however, they interact too easily and a strong horizon limiting the observations energy appears. The most elusive is the astrophysical neutrinos: whenever there is a weak interaction (i.e., nuclear and particle transformation), they appear; since they are almost unstoppable because of their rare interactions, they come directly from the source. The most pivotal messenger, strongly correlated to the other two, is the Cosmic Rays: nuclei of ejected matter; they keep the information on the source composition, interactions, and fate, and the Universe composition and chemical element construction (i.e., the formation of all astrophysical objects, including us).
The Cosmic Rays (CRs) interact with all three forces: electromagnetic, weak, and strong. The last one is responsible for their destruction once they enter our atmosphere. Their passage produces an "air shower." As soon as a CR (primary particle) interacts with an air molecule, other particles are generated ("mesons," mostly Pions and Kaons), which interact as well, creating a particle cascade. The mesons also decay, producing a shower of gammas, electrons, muons (μ), and neutrinos. This process is not eternal because particle daughters subdivide their mother's energy in each step. Hence, once these secondary particles no longer have enough energy, they become absorbed by the air and disappear. The surviving particles reaching the ground cover an extensive area, even kilometers square!
While the density of electrons and gammas reaching the ground delivers the energy information of the primary particle, the muons convey the atomic mass (i.e., what kind of nucleus arrived at us). Both pieces of information are pivotal to understanding the arriving CRs and their diffusion in the Universe. The energy spectrum is well-measured. The mass composition is precisely known only for CRs with energies below 10^{15} eV (HECR), where it is possible to detect the primary directly through satellites. But at higher energies (UHECR), currently up to 10^{21} eV, they are too rare and energetic for satellites, and we need to rely on indirect measurements, such as the muon density on the ground. The air shower development in the atmosphere is so complicated that we must rely on extensive simulations of the particle-air hadronic interaction to interpret the measurements in terms of mass composition. The current models, however, predict much fewer muons of what we observe in the detectors, making the result interpretation unreasonable. This excess is called the *Muon Puzzle*. It is considered as such because the early stages of the air shower development have proven correct! Only on the ground muons have an unpredicted excess.
The project μPPET [mu(**μ**)on **P**robe with J-**PET**; pronounced as the word */muppet/*] plans to solve this puzzle. That is the first experiment dedicated solely to studying it. All Cosmic Ray experiments have tried to solve it so far. Still, there are too many unknown variables (mass composition), and the detector's geometry is optimized for different scientific cases. In particular, studying the puzzle in the guise of the envisioned update of the hadronic interaction models requires detailed information on the muons at the ground, such as track and charge distributions (observables), influenced by the polarizations and inaccessible from other experiments. The polarization of the projectile (i.e., a muon) and/or the target (air molecule) introduces a small correction to the probability of muon interaction, i.e., their production and their trajectories. In the early stages of the air shower, it is negligible, passing unnoticed experimentally. However, having this correction cumulated interaction after interaction, the number of muons is expected to be larger and spreader on the ground.
μPPET will follow two lines of work in parallel: one consists of modifying the hadronic interaction models, and the second provides the necessary measurement to tune it and verify their predictions. The effects of the CR/air polarization is not typically measured in Cosmic Ray experiments and are assumed absent. That's the reason for a synergic measurement in parallel: a first data campaign to have an initial estimation of the discrepancy between predicted and measured muons observables to tune the new models' parameters; a second campaign to increase the statistics and improve the tuning; and a final campaign to verify the predictions. The experimental setup uses the two available J-PETs: a prototype and a finalized one. The prototype is used as a probe with a fixed position and can measure the muon observables with high precision. The finalized can have its scintillator module separated: we will spread them in dedicated configurations (order of 10-50 meters from each other) to reconstruct the shower core at different distances from the probe. Thanks to this core reconstructor mobility, we plan to measure the muon observables and test the new models in different core-probe distances, i.e., as a function of the lateral distribution of particle densities. Whether successful or not, this project will resonate with other experiments. In the former and envisioned case, the puzzle is solved, experiments will try to test the new models and work in synergy with μPPET. Moreover, this might change the design of future Cosmic Ray detectors. In the worst-case scenario, for the first time, we will have detailed measurements of the muon behavior regarding the *Muon Puzzle* issue and a more accurate and correct hadronic interaction model.