Contribution ID: **13** Type: **not specified**

Proton-air interactions at ultra-high energies in muon-depleted air showers with different depths

Thursday 27 June 2024 09:40 (20 minutes)

The hardness of the energy spectrum of neutral pions produced in proton-air interactions at ultra-high energies, above 10^{18} eV, is constrained by the steepness of the distribution of the number of muons in muon-depleted extensive air showers.

In this work, we find that this steepness, quantified by the parameter Λ_μ, evolves with the depth of the shower maximum, $X_{\rm max}$, assuming a universal value for shallow showers and an enhanced dependence on the high-energy hadronic interaction model for deep showers. We show that $X_{\rm max}$ probes the so-called hadronic activity of the first interaction, thus allowing direct access to the energy spectrum of neutral pions in different regions of the kinematic phase space of the first interaction.

We verify that the unbiased measurement of Λ_μ is possible for realistic mass composition expectations. Finally, we infer that the statistical precision in Λ_μ required to distinguish between hadronic interaction models can be achieved in current extensive air shower detectors, given their resolution and exposure.

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Session Classification: Astroparticle Physics