Investigation of Hadronic Interactions at Ultra-High Energies with the Pierre Auger Observatory

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The aim of the Pierre Auger Observatory is the investigation of the nature of cosmic ray particles at ultra-high energies. It can simultaneously observe the longitudinal air shower development in the atmosphere as well as particle densities on the ground. While there are no dedicated muon detectors, techniques have been developed to estimate the number of muons, $N_\mu$, produced by air showers. Both, the longitudinal development, in particular the depth of the shower maximum, $X_{\text{max}}$, and the muon content of air showers are highly sensitive to hadronic interactions at ultra-high energies. Currently, none of the available hadronic interaction models used for simulations of extensive air showers is able to consistently describe the observations of $X_{\text{max}}$ and $N_\mu$ made by the Pierre Auger Observatory.

1 Introduction

At the Pierre Auger Observatory\textsuperscript{1} extensive air showers induced by ultra-high energy cosmic ray particles with energies of $10^{18} - 10^{20}$ eV are investigated. The aim of the experiment is to solve the mysteries on the nature and the sources of these ultra-high energy cosmic ray particles. Since individual cosmic ray primaries and also ultra-high energy secondaries in the startup of the air shower cascade are interacting with our atmosphere at center-of-mass energies up to $\sim 450$ TeV, the Pierre Auger Observatory is also sensitive to the physics of hadronic interactions at center-of-mass energies far beyond the reach of the LHC. We demonstrate the current ability to test existing hadronic interaction models at these energies.

The observatory consists of an array of 1600 water-Cherenkov particle detectors distributed on a surface of 3000 km$^2$ combined with 24 fluorescence telescopes overlooking the atmosphere

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above the surface array in moonless nights. While the advantage of the surface array is a duty cycle of close to 100\%, the fluorescence telescopes, which have a duty cycle of \(\sim 13\%\), provide an almost calorimetric measurement of the energy of the air showers as well as the position of the maximum energy deposition in the atmosphere, \(X_{\text{max}}\).

The Pierre Auger Observatory combines the strengths of the two detection techniques, and can thus achieve an unprecedented level of quality in data analysis. A good example is the measurement of the total flux, which is founded on the purely geometric acceptance of the surface array combined with the almost calorimetric energy reconstruction of the fluorescence telescopes\(^2\). This makes it the first cosmic ray experiment that is able to reconstruct the cosmic ray flux with an absolute minimum of systematic uncertainties induced by Monte Carlo. The resulting total cosmic ray flux is displayed in Figure 1 (left), where it is shown together with the results of other experiments. The spectrum in the energy region of the Pierre Auger Observatory exhibits two important features. Around \(10^{18.5}\) eV there happens a hardening of the spectrum, and above \(\approx 10^{19.6}\) eV a suppression is observed. The former is believed by most theorists to be related to the transition from a galactic to an extragalactic origin of cosmic rays\(^9,10,11,12\). The latter is compatible with the GZK cutoff\(^13,14\), which is caused by interactions of cosmic ray particles with the extragalactic photon field, while it could also be related to the maximum acceleration energy of the cosmic ray source(s).

On the other hand, for other analyses, as for example the reconstruction of the primary mass composition of cosmic rays, the prediction of air shower Monte Carlo simulations are a crucial ingredient\(^15\). The poorly constraint physics of hadronic interactions at the relevant ultra-high energies and phase space regions are currently preventing an unambiguous, or even self-consistent, analysis of the available data. At the same time it is demonstrated that air shower observables are very sensitive to hadronic interaction physics\(^16\). Thus, by using astrophysical constraints on the primary cosmic ray mass composition it is possible to study the features of hadronic interactions at ultra-high energies occurring in the startup of extensive air showers. The observables most sensitive to hadronic interaction physics are the depth of the shower maximum, \(X_{\text{max}}\), and the number of muons on the observation level, \(N_\mu\).

2 The depth of the shower maximum

The depth of the shower maximum, \(X_{\text{max}}\), is one of the most important observables of the telescope detectors. It is reconstructed by fitting a Gaisser-Hillas parameterization to the reconstructed energy deposit profiles\(^17\). With the Pierre Auger Observatory a resolution better
Figure 2: Left panel: Measured muonic signal, $S_\mu$, in water-Cherenkov tanks obtained after subtraction of the electromagnetic signal component. The lower markers are the predictions by QGSJetII for proton and the upper markers for iron induced air showers. The energy of the simulated showers was shifted up by 30%. Right panel: Comparison of the muon reconstruction methods applied to Auger data. The muon number $N_\mu$ is defined as the relative muon number compared to the predictions of QGSJetII, and the energy scale may be varied within the systematic uncertainties, which are indicated as dashed vertical lines.

than 20 g/cm$^2$ for $X_{\text{max}}$ is achieved. In Fig. 1 (right) the measured mean $X_{\text{max}}$ versus energy is compared to predictions from air shower Monte Carlo simulations for different primary cosmic ray particles and hadronic interaction models. The main features of the data of the Pierre Auger Observatory are a slight trend from heavier to lighter composition at low energies, while above $10^{18.2}$ eV this trend is stopped, or maybe even reversed. The data can be described by all hadronic interaction models with a medium or mixed mass composition with $A \sim 7$.

3 The number of muons at the observation level

The Pierre Auger Observatory has no dedicated muon detectors. However, it is possible to indirectly infer the number of muons in the water-Cherenkov tanks of the surface array with several methods. The principle of one technique, which combines the data of the telescopes with that of the surface array, is the subtraction of the electromagnetic part of the air shower, as it is measured by the telescopes, from the signal in the surface array to yield the muon signal. The results of this method are shown in Fig. 2 (left). Even with the energy of the simulations scaled up by 30%, which is just within the systematic uncertainties quoted by the Auger Collaboration, the data are lying beyond the iron predictions. Similar results are obtained with all the other muon measurement methods on the data of the Pierre Auger Observatory, which are summarized in Fig. 2 (right). The muon number larger than the predictions by iron primaries is by itself a strong indication of a deficient hadronic interaction modeling. Furthermore, comparing the results to the $\langle X_{\text{max}} \rangle$ data exhibits a striking incompatibility of the interpretations with the existing interaction models.

All the results discussed here are based on comparisons to simulations performed with QGSJetII. The choice of a different interaction model does not change the findings qualitatively. Even the EPOS model, which predicts the largest muon numbers, cannot fully account for the discrepancies.

4 Summary

It is shown that the two observables of the Pierre Auger Observatory that are most sensitive to hadronic interaction physics at ultra-high energies, $X_{\text{max}}$ and $N_\mu$, do not give a consistent picture when compared to air shower Monte Carlo simulations. While the $\langle X_{\text{max}} \rangle$ data is located...
well in between the predictions for proton and iron, the $N_\mu$ data is located outside of this interval and would favor a mass composition even heavier than iron.

This result clearly points out the deficiency of existing hadronic interaction models to describe cosmic ray data at ultra-high energies. The characteristics of hadronic interactions within the air shower cascade must be different from what is currently assumed in all the models.

With improved constraints on the primary cosmic ray mass composition, observations of this kind can be used to study the relevant properties of hadronic interaction physics at center-of-mass energies up to $\sim 450$ TeV.

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References