Determination of Hadronic Interaction Characteristics with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory measures extensive air showers (EAS) up to the highest energies. One of the biggest challenges in current data analyses is to interpret these data in terms of the primary mass composition. Due to the insufficient constraint of interactions in EAS this is afflicted with large uncertainties. On the other hand, this high sensitivity of EAS to interaction features can be exploited to determine or constrain properties of interactions up to \(\sqrt{s}\) of 450 TeV. We demonstrate how specific EAS observations are suited for this task and thus may contribute to limit the uncertainties in the interpretation of air showers. These are the estimation of the muon number at ground level and the study of the hadronic cross section for particle production via EAS fluctuations.

1. Introduction

The Pierre Auger Observatory is the largest operating cosmic ray detector. It was constructed to study the nature of the highest energy particles known to humankind: ultra-high energy cosmic ray particles. These cosmic ray particles are observed not directly, but via the extensive air shower cascades they initiate in the atmosphere. One of the major advantages of the Pierre Auger Observatory is its hybrid setup. Extensive air showers are observed via two complementary methods. Firstly, the fluorescence light emission caused by the air shower cascade while traversing the atmospheres is recorded with 27 telescopes \([1]\). Secondly, the particles reaching ground level are measured with a surface array of 1660 water Cherenkov detectors, which are arranged on a triangular grid with 1.5 km spacing on a total surface area of \(\approx 3000 \text{ km}^2\) \([2]\).

The surface array enables us to continuously take data and thus acquire a very large exposure. Also the water Cherenkov detectors are very sensitive to the passage of muons and thus various techniques have been developed in the Pierre Auger Collaboration to determine indirectly the muon content of extensive air showers at ultra-high energies \([3, 4]\).

The telescopes allow us to determine the total calorimetric air shower energy with minimal residual model-dependence via measuring the energy deposited in the atmosphere. Also high statistics and precise event-by-event measurement of the shape of the longitudinal energy deposit profiles are very sensitive to the primary mass composition and to details of hadronic interaction characteristics at ultra-high energies \([6]\). An excellent observable characterizing the longitudinal development is the amount of atmospheric material traversed at the point of the maximal energy deposit, \(X_{\text{max}}\).
Figure 1. Description of one golden hybrid event by simulations. Left panel: Longitudinal energy deposit profile. Right panel: Lateral distribution in the surface detector array.

2. Muon Content of Extensive Air Showers

In golden hybrid events extensive air showers are observed independently by the telescopes and the surface detector array. These are ideal conditions to test the overall accuracy of the modeling of extensive air showers [5]. The longitudinal data from the telescope defines the total energy of the event, and air shower profiles can be simulated for different primary particle types to yield excellent descriptions of the longitudinal data (see Fig. 1, left). However, when these simulations are checked also in the surface array, we always find a significant underprediction of the data by all simulations (see Fig. 1, right). This indicates a deficit of muons in the simulations.

There are methods that are directly sensitive to the number of muons in air showers. Several independent methods show that there are indeed too few muons in the simulations. In Fig. 2 the result of two muon measurements are shown and compared to simulations. The data is presented relative to the predictions of the QGSJetII [7] model for proton primary particles. The multivariate method exploits the structure of the time trace in the water Cherenkov detectors. Signals are recorded in 1000 bins of 25 ns length. Single muons produce a characteristic signal with a short rise and fall time, while electromagnetic shower particles produce a smooth background in the time trace. The multivariate analysis uses the fine-structure of the time traces to build an estimator of the number of muons in a tank. The universality method parametrizes the electromagnetic attenuation of air showers cascades in the atmosphere and then determines the muon content with a constant intensity argument: air showers of the same primary energy have to arrive uniformly in direction [8]. The muon fraction is scaled to obtain the constant intensity. This method does not work on an event-by-event basis but needs large datasets. Also, to determine the average electromagnetic signal contribution, the measured value of $\langle X_{\text{max}} \rangle$ is used.

Both methods use complementary aspects of the data and find a muon content significantly above what is expected from simulations. The effect is dependent on the zenith angle of events, which could be related to a dependence on the muon energies. At high zenith angles the muon deficit in the simulations is largest. It is up to 50\% considering primary proton particles, but even for iron it is $\sim 20 - 25\%$.

3. Hadronic Cross Sections

The Pierre Auger Observatory measures event-by-event fluctuation of $X_{\text{max}}$. These fluctuations are directly related to the fluctuation of the depth of the first interaction in the atmosphere. In order to determine the hadronic cross section for the first interaction, the additional fluctuations induced during the shower development following the first interaction have to be subtracted,
which is a model dependent procedure [9]. Thus, we are performing the analysis in several steps.

We first perform a measurements of air shower fluctuations. Since it is known that the primary mass composition has a major impact on air shower fluctuations, we try to reduce the sensitivity to mass composition as much as possible. Firstly, we use only data in the energy range $10^{18} - 10^{18.5}$ eV, where our data is best described by a significant fraction of protons [10]. Secondly, we use only the tail of the $X_{\text{max}}$ distribution at large depths, since heavier primary particles are less penetrating with respect to protons. The remaining dependence on the mass composition and also of a possible photon contamination [11] is evaluated with simulations and included in the systematic uncertainties. In Fig. 3 (left) we show the measurement of the exponential slope of the tail of the $X_{\text{max}}$ distribution, $\Lambda_\eta$. The range of the tail is defined to contain the 20% most deeply penetrating events, which is a definition that can be easily applied also on simulation level.

This measurement is then converted into an estimate of the cross section for particle production, $\sigma_{p-\text{air}}^{\text{prod}}$, of primary cosmic ray protons in the atmosphere. This step necessarily has to rely on air shower modeling. In order to get a consistent result, we change all hadronic cross sections within the models during the air shower simulation process using a smooth modification function in energy above the energies where the models have been tuned to accelerator data. This function is

$$f(E, f_{19}) = 1 + (f_{19} - 1) F(E) \quad \text{with} \quad F(E) = \frac{\lg (E/10^{15} \text{ eV})}{\lg (10^{19} \text{ eV}/10^{15} \text{ eV})}$$

for $E > 10^{15}$ eV. The result of the conversion of $\Lambda_\eta$ to $\sigma_{p-\text{air}}^{\text{prod}}$ is

$$\sigma_{p-\text{air}}^{\text{prod}} = [505 \pm 22(\text{stat}) \pm 28(\text{sys})] \text{ mb}, \quad (1)$$
where the systematic uncertainty comprises the impact of hadronic interaction models, mass composition, event selection, simulations and other effects (c.f. [9] for a detailed discussion). In Fig. 3 (right) the result is compared to other data and model predictions.

4. Conclusion

We summarize the measurements of the Pierre Auger Observatory that are most relevant in the context of determining hadronic interaction characteristics at ultra-high energies. We conclude that precise measurements of extensive air showers at ultra-high energies can have an impact on understanding hadronic interactions at energies beyond what is accessible at accelerators.

The muon measurement based on the data from the surface array indicates a significant deficit of muons in the simulations. It is interesting to note that even a 50% deficit in the total number of muons, accumulated over a very large number of interactions in the air shower cascade, indicates a generally small uncertainty on the level of single interactions. The muon deficit is related to hadronic interaction over a wide range in energies occurring within a particular air shower (down to \sim GeV) and is very sensitive to basically all hadronic particle production processes in the air shower cascade.

The cross section analysis uses hybrid data and is sensitive to the ultra-high energy interactions in air showers. The analysis is performed with minimal sensitivity to a possible non-proton primary cosmic ray component. Telescope acceptance effects are minimized using a fiducial volume selection of air shower geometries. Systematic uncertainties are extensively studied.

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