MEASUREMENTS OF $\mathrm{X_{max}}$ AND TESTS OF HADRONIC INTERACTIONS WITH THE PIERRE AUGER OBSERVATORY

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The Pierre Auger Observatory is designed to detect the particle showers produced in the atmosphere by the most energetic cosmic rays, particles with individual energies up to E$\simeq 10^{20}$ eV. The challenge is to measure their spectrum, arrival directions and mass composition. The depth of the maximum of the longitudinal shower developement ($X_{\max}$) is an indicator of the elemental composition. We present the measurement of the first two moments of the $X_{\max}$ distribution for $E > 10^{18}$ eV. The interpretation in terms of primary masses can only be done by comparison with predictions of hadronic interaction models. The description of hadronic interactions can be tested by determining the muon content of air shower data. Our results at E $\sim 10^{19}$ eV are compared with the predictions of the QGSjetII model for both proton and iron primaries, showing an observed excess of muons with respect to the model.

1 Introduction

Cosmic rays (CR) are a natural beam of ionized atomic nuclei with a rapidly falling energy spectrum that extends up to E $\sim 10^{20}$ eV. To understand the sources and propagation of CRs, the measurement of their flux, elemental composition and distribution of arrival directions is needed. In the highest energy range of the CR spectrum, fluxes are too low for direct observation with satellites or balloon-borne instruments: ground based detectors are used. They observe the particle showers initiated by CRs when interacting with the terrestrial atmosphere. From the point of view of particle physics, the detection of CRs at extreme energies can be regarded as a fixed target collider experiment. The first interactions between primary CRs and atmospheric nuclei reach energies equivalent to p-p collisions at $\sqrt{\mathrm{s}} \simeq 400$ TeV, about one order of magnitude above those accessible with the LHC.

2 The Pierre Auger Observatory

The Pierre Auger Observatory operates in the Ultra High Energy (UHE) range (E>10^{18}eV). Its Southern Site is located in the Mendoza province, in Argentina. The Auger Observatory is a hybrid experiment combining two complementary detection techniques. A 3,000 km^2 surface detector (SD) samples the shower particles reaching ground level with 1660 water-Cherenkov detectors. The SD is overlooked by a fluorescence detector[1] (FD): 27 telescopes at 4 sites detect the fluorescence light emitted along the longitudinal path of the shower. The SD has $\sim$100% duty cycle, and detection efficiency > 97% above 3 EeV for zenith angles < 60°.[2] The signal in each water-Cherenkov detector is recorded as FADC traces from 3 photomultipliers. The FD,

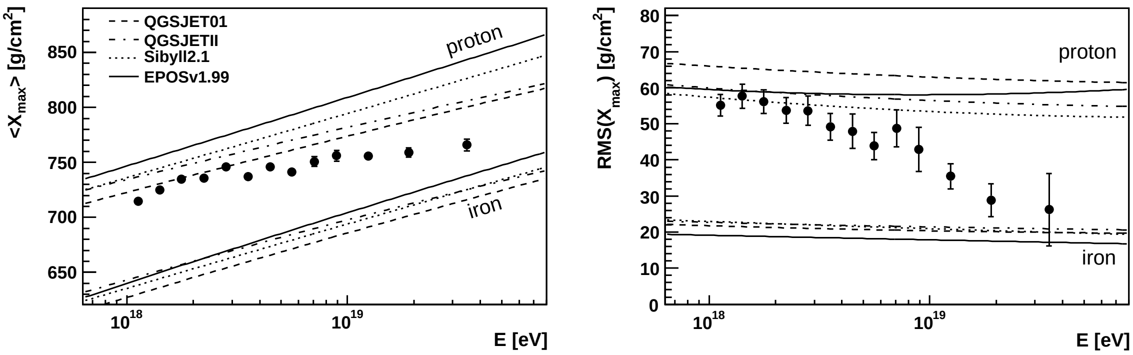

Figure 1: The measured $X_{\max}$ and RMS($X_{\max}$) as a function of the primary energy are compared with air shower simulations using different primary particles and hadronic interaction models. The RMS($X_{\max}$) distribution is obtained after subtracting in quadrature the detector resolution.[6]

which operates in clear moonless nights (duty cycle $\tilde{1}5\%$), can detect CRs down to an energy of $\sim 10^{18}$ eV and is able to observe, within its field of view, the longitudinal profile of the shower. The coexistence of the two detectors combines the high exposure of the SD, yelding high statistics, and the almost calorimetric measurement of the energy of air showers provided by the FD. A subset of high quality hybrid events (golden hybrids), detected and reconstructed independently by the SD and FD, are used to calibrate the SD energy scale on the FD one.[3] The estimate of the total systematic uncertainty on the energy scale is 22%.[4]

3 Measurements of X_{max}

The depth at which the longitudinal developement of the shower reaches its maximum contains information about the mass of the primary CR initiating the shower and about the properties of hadronic interactions. It can be measured with high accuracy by the FD. The average value $\langle X_{\max} \rangle$ depends on the primary energy E and on the number of nucleons A:

$$\langle X_{\max} \rangle = \alpha \left(\ln E - \langle \ln A \rangle \right) + \beta, \tag{1}$$

with α and β depending on the the details of hadronic interactions. Their values are very sensitive to changes in cross-section, multiplicity and elasticity.[5] Eq. 1 is derived from a simple generalization of the Heitler model to showers induced by hadronic primaries, but it provides a good description of the $X_{\max}$ evolution predicted by hadronic models currently in use. In the energy range of interest for the Auger Observatory, α and β can be considered independent of E. Another mass sensitive quantity is RMS($X_{\max}$), expressing quantitatively the shower-to-shower fluctuations of $X_{\max}$. It is expected to decrease with the number of nucleons A. The measurement of $X_{\max}$ and RMS($X_{\max}$) presented in Fig. 1 is based on the analysis of hybrid data collected between December 2004 and March 2009[6]. Hybrids are defined as events observed by the FD and at least one SD station. After quality cuts, 3754 hybrid events are used. The number of events per energy bin is shown in Fig. 2, left. A comparison with four widely used high-energy hadronic interaction models [7,8,9,10] suggests a gradual transition to heavier composition with increasing primary energy (Fig. 1, left). In the simple hypothesis of two mass components, however, the RMS($X_{\max}$) results from the RMS of individual species and from the separation of their $\langle X_{\max} \rangle$: a gradual transition form p to Fe primaries should lead to an increase of RMS($X_{\max}$) above the value predicted for protons.[11] This effect is not observed in the Auger measurements (Fig. 1, right).

The elongation rate, defined as the variation of $X_{\max}$ per decade of energy, is sensitive to changes in composition with energy. A constant elongation rate cannot describe the measured evolution of $\langle X_{\max} \rangle$ with energy. A broken line is used in Fig. 2 (left) to fit the distribution: a change of

82^{+25}_{-21} g/cm^2/decade in the elongation rate occurs at $\log_{10}$(E/eV)=18.24 $\pm$ 0.05. This is close to the energy of the spectral ankle[3] at $\log_{10}(\mathrm{E_{ankle}/eV})$=18.65 $\pm$ 0.09(stat)$^{+0.10}_{-011}$(sys), which is usually interpreted in terms of transition from galactic to extragalactic CRs. This interpretation is supported by the observed change in the elongation rate, under the assumption that hadronic interactions are not significantly changing with energy.

4 Muon content of air showers

The sensitivity of the Auger Observatory to both the electromagnetic and muonic components of air showers, allows us to test predictions of their relative contributions given by hadronic interaction models. The detector cannot, at present, measure separately the muon content of air showers, but several methods have been developed for an indirect estimate of the contribution:

(a) the **universality method**[12], based on the hypothesis that the electromagnetic and muonic signals measured at the ground for a fixed energy and a given distance from the shower axis have a universal dependence on the difference in grammage between the observation level and the shower maximum. The relative normalization of the muonic component can then be determined by requiring the total signal to match the experimental observations;

(b) the **jump method**[13] correlates the signal differences between consecutive bins of the SD FADC traces and the muon fraction of the total signal;

(c) the **smoothing method**[14] finds muon-induced peaks in the FADC traces of the SD stations through an iterative smoothing procedure;

(d) the **golden hybrid analysis**[14] selects, in a set of simulations with the same energy and geometry of a given event, the longitudinal profile that matches most closely the measured one. The simulated SD response is then compared with the SD measurement.

Events selected in the energy range $\log_{10}(\mathrm{E/eV}) = 19 \pm 0.2$ ($\sqrt{s} \simeq 140$ TeV for proton primaries) and zenith $\theta < 50°$ have been analysed to obtain the muonic content at 1000 m from the shower axis.[14] The number of muons N_μ^{rel} relative to the prediction of QGSjetII[9] for protons is shown in Fig. 2 (right). The results obtained with the different methods are compatible with each other.

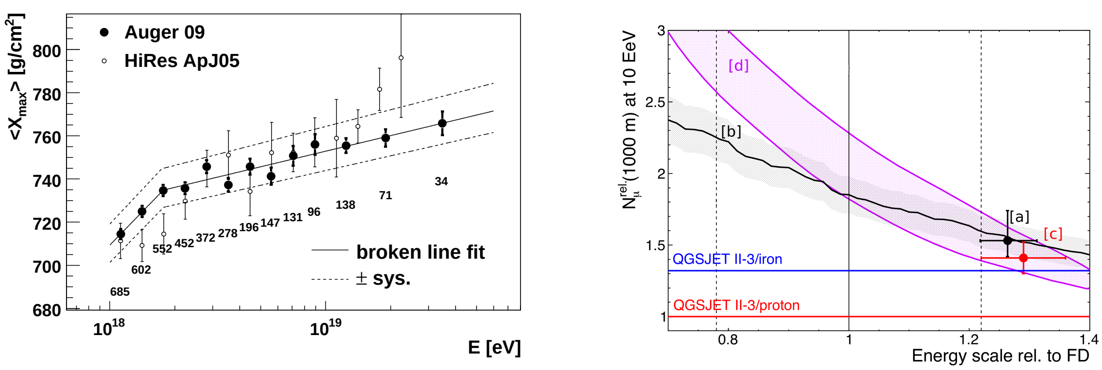

Figure 2: Left: A broken line is used to fit the evolution of $\langle X_{\max}\rangle$ with the logarithm of the primary energy. The change of slope (elongation rate) supports a change in the mass composition of cosmic rays at the ankle. The measurements of $X_{\max}$ published by the HiRes collaboration[15] are shown for comparison. Right: The muon content of E=$10^{19\pm0.2}$ eV air showers is determined at 1000 m from the shower axis with different indirect methods (a-d, see text and references therein) and expressed as a number relative to the prediction of the QGSjetII model for protons primaries. That number is shown as a function of the shift in energy scale with respect to the FD one.

Methods (a) and (c) constrain the energy scale to values higher than the FD scale but compatible with its systematic uncertainty. If the energy is fixed at this new scale, the muon content in the data exceeds the QGSjetII prediction for protons by 30% to 70%. The model prediction for iron primaries ($N_\mu^{rel} = 1.32$, blue horizontal line) is marginally compatible with the results of the methods within their systematic uncertainties. The measurement of $X_{\rm max}$ at the same energy, hovever, is not compatible with QGSjetII predictions for a pure iron composition (Sec. 3). The AMIGA[16] extension of the Auger Observatory (in R&D) will employ scintillation counters buried 2.3 m underground to avoid the detection of the electromagnetic component of air showers. AMIGA will provide, on a fraction of the SD area, a direct measurement of the muonic component that can be used to test and calibrate the indirect methods used so far.

5 Conclusions

The Pierre Auger Observatory is the largest detector currently in operation for the detection of cosmic rays in the UHE range. Its main scientific goal, from the point of view of astrophysics, is to find clues about the sources, acceleration and propagation of cosmic rays. From the point of view of particle physics, it observes, through air showers, collisions up to $\sqrt{s} \simeq$400 TeV, where the properties of particle interactions have large uncertainties and are extrapolated from collider measurements using hadronic interaction models. On the one hand reliable models are required for a precise interpretation of data, in particular for determining the mass composition of CRs, on the other hand the data collected with the Auger Observatory provide a unique test bed for constraining model predictions at extreme energies. The depth of the shower maximum, its fluctuations and the muon content of showers at ground level are important observables related to the elemental composition and are model dependent. The measurement of $X_{\rm max}$ suggests a transition toward increasingly heavier primaries with increasing energies, although the measured RMS($X_{\rm max}$) is smaller than models would predict. The QGSjetII model was tested against data: at $\sim 10^{19}$ eV it fails to describe consistently both $X_{\rm max}$ and muon content at 1000 m from the axis. A deficit of muons is found in the predictions of the QGSjetII model.

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