

Comparison of data from the Pierre Auger Observatory with predictions from air shower simulations: testing models of hadronic interactions

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Abstract. The Pierre Auger Observatory is a hybrid instrument that records the longitudinal, lateral and temporal particle distributions of very high-energy air showers and is sensitive to their electromagnetic and muonic components. Such observables depend on energy and on the type of primary particle that initiates the shower and are sensitive to the hadronic interaction properties. Independent analyses of the combined distributions and direct tests of the predictions of hadronic interaction models are performed at $\simeq 10^{19}$ eV, which corresponds to $\sqrt{s} \simeq 140$ TeV for proton primaries.

Keywords: Ultra High Energy Extensive Air Showers, Hadronic Interactions, Muons

I. INTRODUCTION

The Pierre Auger Observatory is uniquely configured for the investigation of extensive air showers (EAS): with the Fluorescence Detector (FD), we record the longitudinal shower development and measure the shower maximum and the primary energy, while the muonic and electromagnetic components can be measured at ground by the Surface Detector (SD). This information can be used to directly test the predictions of air shower simulations, which due to the indirect nature of EAS measurements are often needed for the interpretation of EAS data. In general, good overall agreement between simulations and measurements is obtained with modern interaction models, but the limits in the modeling of the very high energy hadronic interactions have long been recognized as the largest source of uncertainty [1]. On the other hand, cosmic rays can offer unique information on these interactions in an energy and phase space region not accessible to man-made accelerators.

In this work, we will test the predictions of hadronic interaction models by (a) measuring the muon content of the showers, both by a global method exploiting the shower universality features and by analyses of the temporal particle distributions in the SD and (b) performing direct tests on the simulation of individual hybrid events detected by the Pierre Auger Observatory. The results presented here are based on the data collected with the Pierre Auger Observatory from January 2004 to December 2008. They extend the analysis of [2] to a larger data set and additional,

independent analysis methods.

II. N_μ MEASUREMENT USING AIR SHOWER UNIVERSALITY

The universality of high-energy showers allows us to describe the surface detector signal at a lateral distance of 1000 m from the core as function of the primary energy E , stage of shower evolution $DX \equiv X - X_{\max}$, and overall normalization of the muon content [3]. This universality holds to $\sim 10\%$ for QGSJET II [5] and SIBYLL 2.1 [6] as high-energy interaction models. Denoting the electromagnetic signal by S_{EM} and the muon signal by S_μ , whose evolution with shower age is universal, one can write

$$S_{MC}(E, \theta, \langle X_{\max} \rangle) = S_{EM}(E, \theta, DX) + N_\mu^{\text{rel}} S_\mu^{\text{QGSJET II, P}}(10^{19} \text{ eV}, \theta, DX) \quad (1)$$

where N_μ^{rel} is defined as the number of muons relative to that of QGSJET II proton showers at 10^{19} eV and $S_\mu^{\text{QGSJET II, P}}$ is the muon signal predicted by QGSJET II for proton primaries. Since $\langle X_{\max} \rangle$ is known from FD measurements, the only unknown in Eq.(1) is N_μ^{rel} , which can be measured at a reference energy $E_0 = 10$ EeV using the isotropy of the cosmic ray flux and the angular dependence of $S_{MC}(E_0, \theta)$ through N_μ^{rel} [2], [4]. Analyzing the full data set, the muon number relative to proton-QGSJET II is

$$N_\mu^{\text{rel}}(10 \text{ EeV}) = 1.53_{-0.07}^{+0.09} (\text{stat.})_{-0.11}^{+0.21} (\text{syst.}).$$

The systematic error includes the remaining primary particle-dependence of the electromagnetic signal as well as the effect of shower-to-shower fluctuations and the uncertainty on $\langle X_{\max} \rangle$. Knowing $N_\mu^{\text{rel}}(10 \text{ EeV})$ and the measured mean depth of shower maximum, the signal size at $\theta = 38^\circ$ can be calculated

$$S_{38}(10 \text{ EeV}) = 38.9_{-1.2}^{+1.4} (\text{stat.})_{-1.8}^{+1.6} (\text{syst.}) \text{ VEM},$$

which corresponds to assigning showers a 26% higher energy than that of the current FD calibration [7].

III. N_μ FROM THE FADC TRACES

The separation of the muonic and electromagnetic components of the SD signal relies on the FADC traces recorded by each of the 3 PMTs of the SD detectors. Each trace is sampled at a frequency of 40 MHz [8]. As a typical muon from a UHECR shower deposits much more energy (≈ 240 MeV) in a water tank than

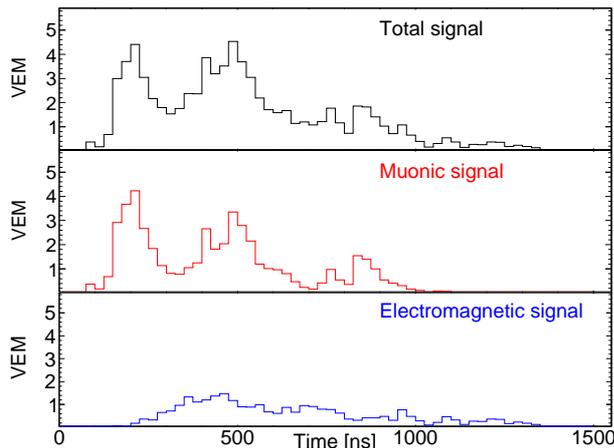


Fig. 1: Example of a simulated FADC trace in one station of the surface detector. From top to bottom: total trace, muonic and EM components. Shown is the tank signal from a proton shower of $\theta = 45^\circ$ and $E = 10^{19}$ (eV) at 1000 m from the core.

an electron or photon ($\lesssim 10$ MeV), spikes are produced over the smoother electromagnetic background in the FADC time traces, see Fig. 1. Thus, muons manifest themselves as sudden variations in the signal. High-energy photons in a shower can produce a sudden increase of the electromagnetic signal similar to that of a muon: their contribution is estimated to be $\lesssim 10\%$.

A. The jump method

To extract muon spikes, we define the FADC jump v as the difference of FADC values of two consecutive time bins [9]. The main idea is that of evaluating the sum of the jumps larger than a threshold v_{thr} which is determined by finding the best compromise between muon selection efficiency and electromagnetic contamination. The raw jump integral

$$\mathcal{J}(v_{\text{thr}}) = \int_{v_{\text{thr}}}^{\infty} \left(\frac{dN}{dv} \right) v dv = \sum_{\substack{v > v_{\text{thr}} \\ t_i, \text{ADC bin}}}^{\infty} v(t_i) \quad (2)$$

is then corrected to calibrate our estimator in terms of number of muons by a factor $\eta(E, \theta, r)$ which depends on the primary energy E , the zenith angle θ , and the distance r of the detector from the shower core.

Monte Carlo simulations based on CORSIKA [10] were used to derive the dependences of the correction factor on the shower parameters and to estimate the possible bias for ultra-high energies and for distances close to the core. The number of muons at 1000 m is determined with a resolution close to 20% and systematic biases below 7%. The relative difference between the simulated and the estimated number of muons is shown in Fig. 2 for different primary particles.

B. The smoothing method

The electromagnetic (EM) contribution to the signal in the surface detectors can be estimated by a smoothing

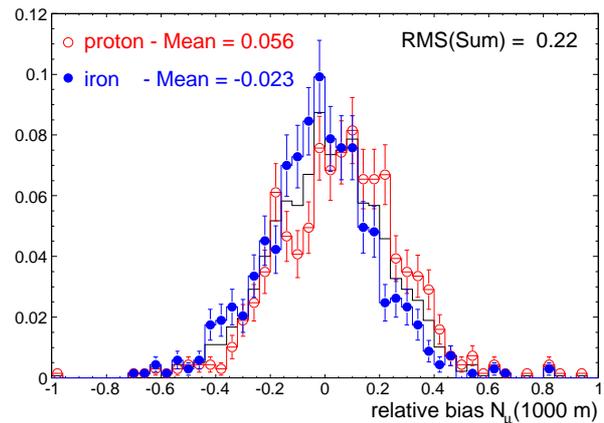


Fig. 2: Dependence of the relative difference between the simulated and the estimated number of muons on the primary particle. The results are presented for 10 EeV energy showers simulated with QGSJET II and zenith angles up to 50° .

method. The total trace recorded by the FADCs of the 3 PMTs in each station is averaged over a preset number of consecutive time bins N_{bin} . Any positive difference between the original trace and the smoothed signal is assigned to the muon component and subtracted from the signal; then the whole procedure is applied again for a number of iterations N_{iter} . Using Monte Carlo simulations, the best parameters $[N_{\text{bin}}, N_{\text{iter}}]$ are determined as those minimizing the bias in the evaluation of the EM component for both proton and iron primaries, and for the largest possible angular range.

Based on simulations, a correction factor $\xi(E, \theta, r)$ is determined that depends on the energy of the primary particle, its zenith angle and the distance to the shower core. For $E > 3$ EeV (full efficiency of the SD) and distances around 1000 m from the core, the EM contribution to the signals is evaluated with a resolution of 23% and a systematic uncertainty below 8%, irrespectively of the primary energy and composition. The relative difference between the estimated and expected EM signals is shown in Fig. 3.

The relative difference $\Delta(S_{\text{EM}}/E)$ between the EM signal reconstructed from data and the QGSJET II prediction assuming all primaries are protons (red empty symbols) or iron (blue filled circles) is shown in Fig. 4. Due to an almost linear energy scaling of the EM shower signal, this discrepancy could be removed by assigning showers a 29% higher energy than from FD calibration. Alternatively, the discrepancy could also be related to an incorrect description of the lateral distribution of EM particles in the simulation.

The muon component in each detector is derived by difference, after having evaluated the EM one, with systematic uncertainties below 8% and a resolution close to 20%.

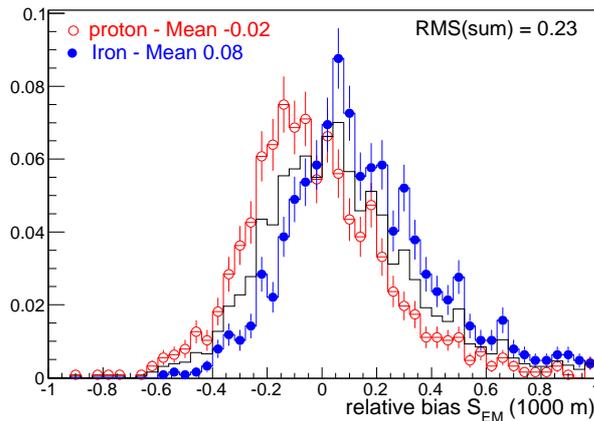


Fig. 3: The dependence of the relative deviation between the simulated and the estimated EM signals on the primary particle. The results are presented for 10 EeV energy showers and zenith angles up to 50° .

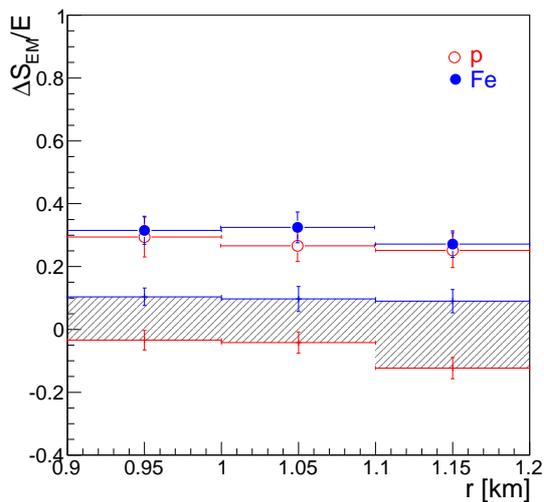


Fig. 4: The relative difference between the EM signals in data and in the simulation (open and filled symbols indicate the use of proton or iron primaries in the simulation, respectively). The systematic uncertainty for S_{EM} (10 EeV and 38° showers) is shown by the shaded band.

IV. INDIVIDUAL HYBRID SIMULATION

The FD and SD signals can be compared to the model predictions on an event-by-event basis with a technique based on the simulation of individual high quality hybrid events. The shower simulations are done using SENECA [11] and QGSJET II as high energy hadronic interaction model. The surface detector response has been simulated with GEANT4 and extensively tested [12]. We use hybrid events with $18.8 < \log_{10}(E/\text{eV}) < 19.2$ that satisfy the quality cuts used in the FD-SD energy calibration and X_{max} analyses [7], [13]. Each event is at first simulated 400 times using the geometry and energy

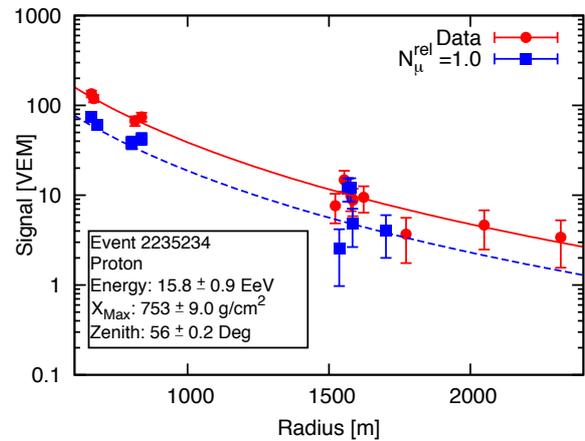
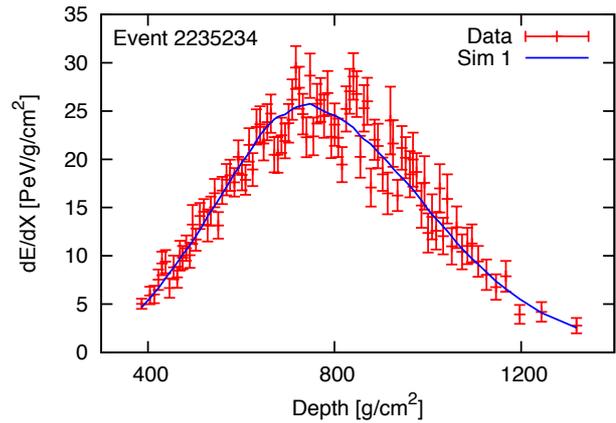


Fig. 5: The observed longitudinal (top panel) and lateral (bottom panel) profiles for one of the hybrid events. The best-matching simulation is shown by the full (top) and dashed (bottom) line (without rescaling of the muon number relative to the model prediction).

given by the hybrid reconstruction of the event. The primary is taken as proton or iron as is most probable based on the measured X_{max} of the event. The three simulated showers with the lowest χ^2 with respect to the FD data are then re-simulated using a lower thinning level to have a high quality simulation of the particles reaching ground. Finally, the actual detector response to each of the simulated events is obtained using [14]. The longitudinal profiles and the lateral distribution functions variation among the three simulations is ≈ 5 and 15%, respectively. The measured longitudinal profile together with that of the best-matching simulated event is shown in Fig. 5 (top panel) for one representative event; in the bottom panel, the measured tank signals are compared to those of the simulated event.

An overall rescaling of the surface detector signals results in a residual discrepancy which increases approximately linearly with $\sec\theta$ of the events; a possible interpretation of this deficit of signal is a lack of muons in the simulations. The preferred energy and muon shift within the Golden Hybrid method can be found determining for each event the reconstructed $S(1000)$,

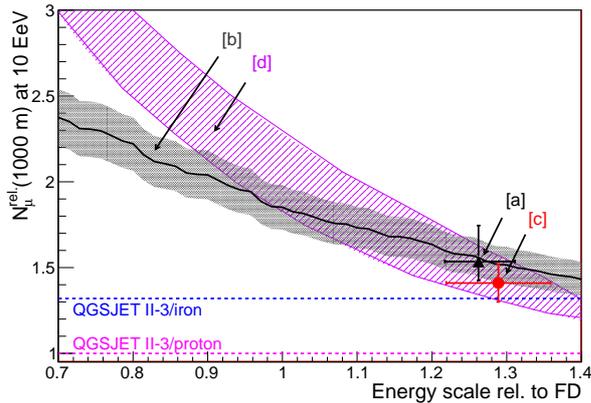


Fig. 6: Number of muons at 1000 m relative to QGSJET-II/proton vs. the energy scale from [a] the universality method (triangle); [b] the jump method (filled area); [c] the smoothing method (circle); [d] the golden hybrid analysis (dashed area). The events have been selected for $\log_{10}(E/eV) = 19.0 \pm 0.02$ and $\theta \leq 50^\circ$. According to the tested model, Iron primaries give a number of muons 1.32 times bigger than that from protons (horizontal lines in the figure).

as a function of the EM and muonic renormalizations, by performing the detector simulations and event reconstruction with individual particle weights adjusted according to the rescaled values. The best rescaling is taken to be that which minimizes the χ^2 between simulated and observed $S(1000)$'s for the ensemble of events. The “one- σ ” contour is found by propagating the statistical uncertainties from the best fit as well as the systematic uncertainties. As can be seen in Fig. 6, there is a strong correlation between the two parameters and the χ^2 minimum is quite broad.

V. RESULTS

The derived number of muons relative to that predicted by QGSJET-II for proton primaries and the energy scale with respect to the fluorescence detector are shown in Fig. 6 for 10 EeV primaries with zenith angle below 50° . The results of all four analysis methods are compatible with each other. The analysis based on shower universality yields a measure of the energy scale which is almost independent of the fluorescence detector calibration, fixing it to $E' = 1.26_{-0.04}^{+0.05}(\text{syst.}) \times E_{FD}$; the smoothing technique constrains the relative energy scale to a value $E' = (1.29 \pm 0.07(\text{syst.})) \times E_{FD}$ from the analysis of the electromagnetic signals alone. The two energy scales agree with each other and are compatible with the currently used FD energy assignment that has a systematic uncertainty of 22% [15]. Adopting the energy scale E' , the analyses agree with the conclusion of a muon signal 1.3–1.7 times higher than that predicted by QGSJET-II for protons. With this energy scale, the results indicate a muon deficit in simulated showers, being only marginally compatible with the prediction

of QGSJET-II for primary iron ($N_\mu^{\text{rel}}=1.32$) within the systematic uncertainties of the different methods used to derive the muon contribution. The observed mean and distribution of the depth of maximum of the showers, however, is clearly at variance with the predictions of QGSJET or SIBYLL for a pure iron composition [16].

The results presented here are obtained at a lateral distance of 1000 m. The rescaling factor found for the muon density does not necessarily apply to the total number of muons in a shower as it is not known how well the models reproduce the lateral distribution of muons. Moreover, the energy scale found in this work is based on the assumption of a correct reproduction of the lateral distribution of EM particles by simulations made with EGS4 [17] in combination with the hadronic models QGSJET and SIBYLL.

Recent work on hadronic interactions [18] has shown that an increase of the predicted muon number of EAS can be obtained if the description of baryon-pair production in hadronic interactions is modified.

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