Interpretation of the signals produced by showers from cosmic rays of 10^{19} eV observed in the surface detectors of the Pierre Auger Observatory

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Abstract: Muons in extensive air showers are messengers of the hadronic-shower core whose simulation is subject to large theoretical uncertainties due to our limited knowledge of multi-particle production in hadronic interactions. Different methods of deriving the fraction of the signal observed in the surface detectors coming from either the muonic or electromagnetic shower components are used to compare the data from the Pierre Auger Observatory with predictions of Monte Carlo simulations. The observations are quantified relative to the predictions obtained with QGSJET II and FLUKA as interaction models. The predicted number of muons at 1000 m from the shower axis is lower than that found in data, and the energy that would have to be assigned to the surface detector signal, based on shower simulations, is systematically higher than that derived from fluorescence observations.

Keywords: muons, hadronic interactions, ultra high energy extensive air showers, muon deficit, simulations

1 Introduction

The Pierre Auger Observatory is a powerful detector for studying extensive air showers at very high energy. The combination of the fluorescence detector (FD) and surface detector array (SD) of the Observatory allows the simultaneous measurement of several observables of showers, providing opportunities to cross-check our current understanding of the physics of air showers. Many features of air showers depend directly on the characteristics of hadronic interactions which are unknown at very high energy and in phase space regions not covered in accelerator experiments. For example, recent work has quantified the sensitivity of the number of muons in ultra-high-energy air showers to several properties of hadronic interactions, including the multiplicity, the charge ratio (the fraction of secondary pions which are neutral), and the baryon anti-baryon pair production [1, 2]. Using models of hadronic interactions that do not provide a good description of shower data might lead to incorrect conclusions about the mass and the energy assignment being drawn from measurements.

In this work the data of the Pierre Auger Observatory is compared to showers simulated using the interaction model QGSJET II.03 [3], which has become a standard reference model for air-shower experiments. Updates are provided to several methods presented previously [4], and a new method is introduced. In Sec. 2, the data from the surface and fluorescence detectors is compared simultaneously, on an event-by-event basis, to the results of simulations. In Sec. 3, the time structure of the particle signals in the surface detectors and a universal property of air showers are used to estimate the number of muons in the data. Finally, in Sec. 4, the ground signals of simulated events are matched to those measured by rescaling the number of muons arising from hadronic processes and changing the energy assignment in simulated showers.

2 Study of Individual Hybrid Events

At the Auger Observatory, thousands of showers have been recorded for which reconstruction has been possible using both the FD and SD. These hybrid events have been used to construct a library of simulated air-shower events where the longitudinal profile (LP) of each simulated event matches a measured LP. The measured LP constrains the natural shower-to-shower fluctuations of the distribution of particles at ground. This allows the ground signals of simulated events to be compared to the ground signals of measured events on an event-by-event basis.

Hybrid events were selected using the criteria adopted for the energy calibration of the SD [5] in the energy range $18.8 < \log(E) < 19.2$ recorded between 1 January 2004 and 31 December 2008. 227 events passed all cuts. Air showers were simulated using SENECA [6] with QGSJET II and FLUKA [7] as the high- and low-energy event generators. For every hybrid event, three proton- and three iron-initiated showers were selected from a set of 200 simulated showers for each primary type. The energy

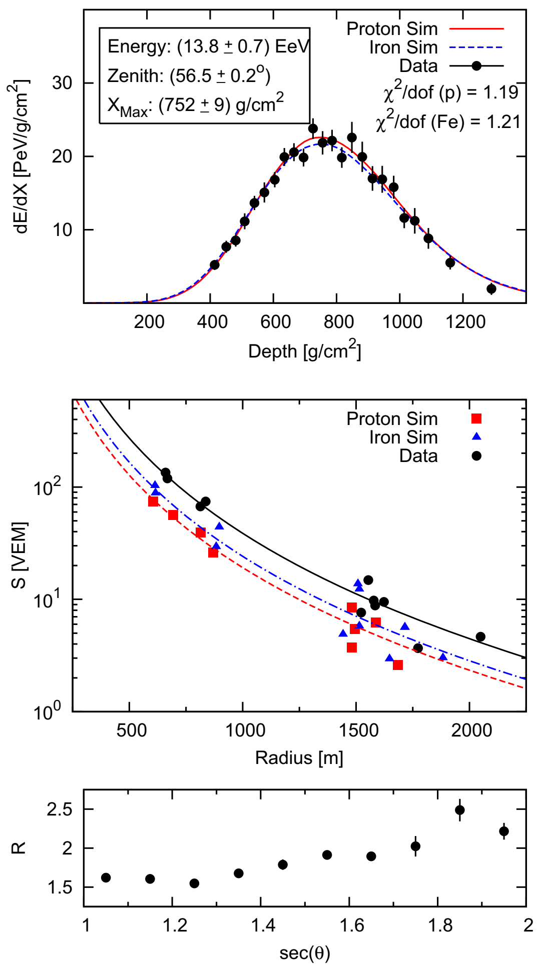

Figure 1: *Top panel:* A longitudinal profile measured for a hybrid event and matching simulations of two showers with proton and iron primaries. *Middle panel:* A lateral distribution function determined for the same hybrid event as in the top panel and that of the two simulated events. *Bottom panel:* R, defined as $\frac{\mathrm{S}(1000)_{\mathrm{Data}}}{\mathrm{S}(1000)_{\mathrm{Sim}}}$, averaged over the hybrid events as a function of secθ.

and arrival direction of the showers matches the measured event, and the LPs of the selected showers have the lowest χ^2 compared to the measured LP. The measured LP and two selected LPs of an example event are shown in the top panel of Fig. 1.

The detector response for the selected showers was simulated using the Auger $\overline{\text{Off}}\underline{\text{line}}$ software package [8, 9]. The lateral distribution function of an observed event and that of two simulated events are shown in the middle panel of Fig. 1. For each of the 227 events, the ground signal at 1000 m from the shower axis, S (1000), is smaller for the simulated events than that measured. The ratio of the measured S (1000) to that predicted in simulations of showers with proton primaries, $\frac{\mathrm{S}(1000)_{\mathrm{Data}}}{\mathrm{S}(1000)_{\mathrm{Sim}}}$, is 1.5 for vertical showers and grows to around 2 for inclined events; see the bottom panel of Fig. 1. The ground signal of more-inclined events is muon-dominated. Therefore, the increase of the discrepancy with zenith angle suggests that there is a deficit of muons in the simulated showers compared to the data. The discrepancy exists for simulations of showers with iron primaries as well, which means that the ground signal cannot be explained only through composition.

3 Estimate of the Muonic Signal in Data

3.1 A multivariate muon counter

In this section, the number of muons at 1000 m from the shower axis is reconstructed. This was accomplished by first estimating the number of muons in the surface detectors using the characteristic signals created by muons in the PMT FADC traces and then reconstructing the muonic lateral distribution function (LDF) of SD events.

In the first stage, the number of muons in individual surface detectors is estimated. As in the *jump method* [4], the total signal from discrete jumps

$$J = \sum_{\text{FADC bin } i} \underbrace{(x_{i+1} - x_i)}_{\text{jump}} \mathbb{I}\{x_{i+1} - x_i > 0.1\} \qquad (1)$$

was extracted from each FADC signal, where x_i is the signal measured in the ith bin in Vertical Equivalent Muon (VEM) units, and the indicator function $\mathbb{I}\{y\}$ is 1 if its argument y is true and 0 otherwise. The estimator J is correlated with the number of muons in the detector, but it has an RMS of approximately 40%. To improve the precision, a multivariate model was used to predict the ratio $\eta = (N_\mu + 1)/(J + 1)$. 172 observables that are plausibly correlated to muon content, such as the number of jumps and the rise-time, were extracted from each FADC signal. Principal Component Analysis was then applied to determine 19 linear combinations of the observables which best capture the variance of the original FADC signals. Using these 19 linear combinations, an artificial neural network (ANN) [10] was trained to predict η and its uncertainty. The output of the ANN was compiled into a probability table $P_{\mathrm{ANN}} = P(N_\mu = N \,|\, \text{FADC signal})$. The RMS of this estimator is about 25%, and biases are also reduced compared to the estimator J.

In the second stage of the reconstruction, a LDF

$$\overline{N}(r, \nu, \beta, \gamma) = \exp\left(\nu + \beta \log \frac{r}{1000\,\mathrm{m}} + \gamma \log\left(\frac{r}{1000\,\mathrm{m}}\right)^2\right) \qquad (2)$$

is fit to the estimated number of muons in the detectors for each event, where r is the distance of the detector from the shower axis and ν, β, and γ are fit parameters. The number of muons in each surface detector varies from the LDF according to the estimate P_{ANN} and Poisson fluctuations. The fit parameters, ν, β, and γ, have means which depend on the primary energy and zenith angle as well as variances arising from shower-to-shower fluctuations. Gaussian prior distributions with energy- and zenith-dependent means were defined for the three fit parameters. All the parameters were estimated using an empirical Bayesian approach: three iterations were performed between (i) finding the maximum *a posteriori* estimate $\widehat{\nu}_i$, $\widehat{\beta}_i$, and $\widehat{\gamma}_i$ for each shower i given the fixed priors, and (ii) re-estimating the priors given the fixed parameter estimates $\widehat{\nu}_i$, $\widehat{\beta}_i$, and $\widehat{\gamma}_i$.

The value of the muonic LDF at 1000 m, $\exp(\widehat{\nu})$, is highly correlated with $N_\mu(1000)$, the number of muons in surface detectors 1000 m from the shower axis. The RMS of $\exp(\widehat{\nu})$ in showers simulated using QGSJET II is 12% and 5% for proton and iron primaries. To correct several biases that depend on the energy and zenith angle of the showers, a quadratic function $f\big(\exp(\widehat{\nu}), \widehat{\theta}\big)$ was tuned on a library of showers simulated using QGSJET II with simulated detector response. The final estimator $\widehat{N}_\mu(1000) = f\big(\exp(\widehat{\nu}), \widehat{\theta}\big)$ has a systematic uncertainty below $50°$ of 6% from uncertainty in the composition and $^{+10\%}_{-0\%}$ from uncertainty in the hadronic models, determined by reconstructing showers simulated using EPOS 1.6. The total systematic uncertainty decreases with the zenith angle: at $\theta = 55°$ it is $^{+9\%}_{-3\%}$.

3.2 Universality of $S_\mu/S_{\rm em}$ behavior on $X^{\rm v}_{\rm max}$

The ratio of the muonic signal to the electromagnetic (EM) signal, $S_\mu/S_{\rm em}$, at 1000 m from the shower axis exhibits an empirical universal property for all showers at a fixed vertical depth of shower maximum, $X^{\rm v}_{\rm max}$ [11]. $S_\mu/S_{\rm em}$ is independent of the primary particle type, primary energy, and incident zenith angle. The dependence of $S_\mu/S_{\rm em}$ on $X^{\rm v}_{\rm max}$ can be described by a simple parameterization which leads to the following expression for the muonic signal in showers with zenith angle between $45°$ and $65°$

$$S^{\rm fit}_\mu = \frac{{\rm S}\,(1000)}{1 + \cos^\alpha(\theta)/\left((X^{\rm v}_{\rm max}/A)^{1/b} - a\right)}\,, \qquad (3)$$

where ${\rm S}\,(1000)$ is as defined above, θ is the zenith angle, $\alpha = 1.2$, and A, a and b are fit parameters [12]. The estimation of the muonic signal in data is complicated by the dependence of the fit parameters A, a, and b in Eq. (3) on the choice of hadronic interaction model. This dependence gives rise to a systematic uncertainty in the measurement of the muonic signal in data which is difficult to quantify due to the uncertainty in properties of hadronic interactions. This problem can be overcome with an additional phenomenological consideration: for showers with zenith angles above $45°$, the fraction of the EM signal coming from the decay and interactions of muons rapidly increases. As shown in [13], different models of hadronic interactions are in agreement on the $S_\mu/S_{\rm em}$ ratio for showers with zenith angle above $45°$, since $S_\mu/S_{\rm em}$ increasingly reflects the equilibrium between muons and their EM halo.

The fit in Eq. (3) provides an unbiased estimate of both the muonic and EM signals. The RMS of the muonic signal in showers simulated using CORSIKA [14] is less than 5% and 3% for proton and iron primaries [12]. The systematic uncertainty of S_μ from uncertainty in the hadronic models is estimated to be 6%, determined by the application of the

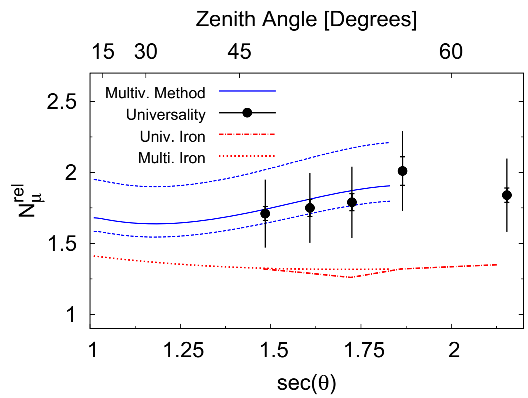

Figure 2: The number of muons estimated at $1000\,{\rm m}$ in data relative to the predictions of simulations using QGSJET II with proton primaries. The results obtained using the multivariate method are shown as the solid line with systematic uncertainties as the dashed lines. The results obtained using the universality of $S_\mu/S_{\rm em}$ are shown as circles with statistical and systematic uncertainties. The results when the methods are applied on a library of iron-initiated showers are shown as the dot and dash-dot lines.

parameterization of Eq. (3) using QGSJET II on showers simulated using EPOS 1.99. The systematic uncertainty of S_μ from event reconstruction is 14% at 10^{19} eV, determined through complete shower simulation and reconstruction using Auger $\overline{\rm Off}\underline{\rm line}$. The systematic uncertainty from event reconstruction is dominated by the systematic uncertainty of ${\rm S}\,(1000)$, with only a few percent coming from the uncertainty of $X^{\rm v}_{\rm max}$ and the zenith angle.

3.3 Application to data

By applying the multivariate and the universality methods to data collected between 1 January 2004 and 30 September 2010, a significant excess of muons is measured compared to the predictions of simulations using QGSJET II; see Fig. 2. The multivariate method was applied to SD events over the energy range $18.6 < \log{(E)} < 19.4$ and $0° - 57°$. The universality method was applied to hybrid events over the energy range $18.8 < \log{(E)} < 19.2$ and $45° - 65°$. For both methods, the excess is estimated here relative to showers simulated with proton primaries.

The multivariate method is used to determine the number of muons, $N_\mu(1000)$. The relative excess is angle-independent, to within 3%, until about $40°$, above which it increases. In particular, at $\theta = 38°$ the excess is $\big(1.65^{+0.26}_{-0.10}\big)$ and at $\theta = 55°$ the excess is $\big(1.88^{+0.17}_{-0.06}\big)$. The universality of $S_\mu/S_{\rm em}$ for fixed $X^{\rm v}_{\rm max}$ is used to estimate the total muonic signal. For $45° - 53°$, the relative excess is $(1.76\ \pm\ 0.04({\rm stat.})\ \pm\ 0.29\,({\rm syst.}))$, while for $53° - 65°$ the discrepancy rises to $(1.89\ \pm\ 0.04\ \pm\ 0.28)$.

4 Discussion

As demonstrated in the analyses, and shown in Figs. 1 and 2, simulations of air showers using QGSJET II with pro-

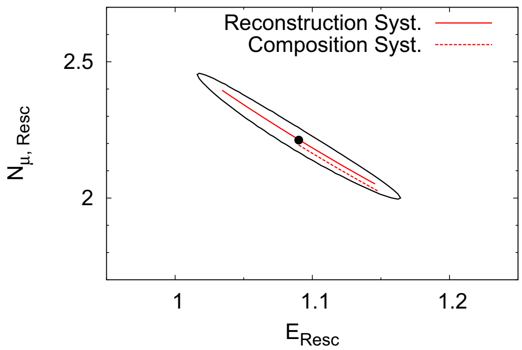

Figure 3: The one-sigma contour of the fit to $N_{\mu,\mathrm{Resc}}$ and E_{Resc} from the simple matching of the ground signals in simulated and measured hybrid events. The systematic uncertainties from reconstruction and composition are shown as solid and, slightly offset, dashed lines.

ton and iron primaries underestimate both the total detector signal at ground level and the number of muons in events collected at the Pierre Auger Observatory. These discrepancies could be caused by an incorrect energy assignment within the 22% systematic uncertainty of the energy scale of the Auger Observatory and/or shortcomings in the simulation of the hadronic and muonic shower components.

To explore these potential sources of discrepancy, a simple modification of the ground signals was implemented in the simulated hybrid events of Sec. 2. The uncertainty in the energy scale motivates the rescaling of the total ground signal by a factor E_{Resc}, and the muon deficit motivates a rescaling of the signal from hadronically produced muons by a factor $N_{\mu,\mathrm{Resc}}$. The rescaled muonic and EM components of $\mathrm{S}\,(1000)$, S_μ and S_{EM} – both defined for proton primaries – modify the ground signal

$$\mathrm{S}\,(1000)_{\mathrm{Sim}} = E_{\mathrm{Resc}}^{0.92}\, N_{\mu,\mathrm{Resc}}\, S_{\mu,\mathrm{Sim}} + E_{\mathrm{Resc}}\, S_{\mathrm{EM,Sim}}\ , \quad (4)$$

where the exponent 0.92 is the energy scaling of the muonic signal predicted by simulations. The rescaling factors were applied uniformly to all events. This represents a simplistic modification, and $N_{\mu,\mathrm{Resc}}$ does not reflect any changes in the attenuation and lateral distribution of muons. However, both the attenuation and LDF would change if, for example, the energy spectrum of muons predicted by simulations is not in agreement with the data.

E_{Resc} and $N_{\mu,\mathrm{Resc}}$ were determined simultaneously by making a maximum-likelihood fit between the modified, simulated $\mathrm{S}\,(1000)$ and the measured $\mathrm{S}\,(1000)$ for the ensemble of hybrid events. The best fit values of $N_{\mu,\mathrm{Resc}}$ and E_{Resc} are $\left(2.21 \pm 0.23\,(\mathrm{stat.})\ ^{+0.18}_{-0.23}\,(\mathrm{syst.})\right)$ and $\left(1.09 \pm 0.08\ ^{+0.08}_{-0.06}\right)$ respectively; see Fig. 3. The systematic uncertainties arise from uncertainty in the composition and event reconstruction.

The signal rescaling in simulated hybrid events is fundamentally different from the other methods. The observational muon enhancement, N_μ^{rel}, which includes all muons, cannot be compared directly to $N_{\mu,\mathrm{Resc}}$, which represents an increase of only the hadronically produced muons and their decay products. In addition, the potential increase of N_μ^{rel} with zenith angle suggests that a global rescaling of the ground signal from muons is overly simplistic.

In summary, all of the analyses show a significant deficit in the number of muons predicted by simulations using QGSJET II with proton primaries compared to data. This discrepancy cannot be explained by the composition alone, although a heavy composition could reduce the relative excess by up to 40%. The purely-observational estimation of the muonic signal in data, using the signal traces of surface detectors and universal properties of air showers, is compatible with results previously presented and the results obtained from inclined showers [4, 15, 16]. The increased sophistication of the methods gives further weight to the previous conclusions: at the current fluorescence energy scale, the number of muons in data is nearly twice that predicted by simulations of proton-induced showers. The update and application to recent data of the constant intensity cut with universality method and the "smoothing method" are in progress. The possible zenith angle dependence of N_μ^{rel} suggests that, in addition to the number, there may also be a discrepancy in the attenuation and lateral distribution of muons between the simulations and data.

An extension of the studies using EPOS 1.99 is in progress.

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