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Improving the universality reconstruction with independent measurements by water-Cherenkov detectors and muon counters

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Prior work has demostrated that particle showers produced by cosmic rays can be well described by a universal model. The secondary particles at the observation level can be modelled with four components: the well known electromagnetic and muonic components, the contribution from the electromagnetic halo of muons, and the electromagnetic particles originating from pion decays close to ground, which closely follow the development of the muonic component. Due to the large quantity of particles produced, these distributions can be described with three parameters: the total energy E of the primary, the depth of maximum shower developement $X_{\max}$, and the muon content R_μ. E and $X_{\max}$ are primarily governed by the pure electromagnetic component, whereas the muon scale (R_μ) depends on primary particle composition and affects the other three components. Although reconstruction of these macroscopic parameters is already viable with a single detector type (e.g. an array of water-Cherenkov detectors), large correlations between the quantities are apparent and must be taken into account when interpreting the data. Additional muon counters allow for an independent measurement of the muon number at ground level, which aids in overcoming degeneracy and reduces systematic uncertainties due to the hadronic interaction model used. The procedure is exemplified for the case of the Pierre Auger Observatory by parameterizing the signals produced by particles in the array of water-Cherenkov detectors paired with underground muon counters. The universal parameterizations allow us to estimate E and R_μ independently on an event-by-event basis. The results of incorporating muon detectors demonstrates e.g. the possibility of an unbiased energy estimation based only on a universal description of showers.

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1. Universality of extensive air showers

Previous work has shown that hadronic primary extensive air showers (EAS) produced by high energy cosmic ray primaries can be universally described with good accuracy [1, 2]. This universal description, named Shower Universality, is built assuming only a few parameters in the description of EAS: the primary energy E, the depth of the shower maximum $X_{\max}$, and an overall ratio of the muon content R_μ. The goal is to describe the shower produced by a primary particle by measuring its secondary particles. Previous work [2, 3, 4] includes a parametrization of signals and their associated time structure in a surface water-Cherenkov detector following the universal description of EAS.

In this paper, the model is extended to a hybrid detector that combines the information of a surface water-Cherenkov detector with that of a muon counter, which is buried to shield against non-muonic particles. The direct measurement of the muonic component improves the resolution of shower parameters and also allows for good estimation of mass composition.

2. Signal model concept

To build the universality model, an extended library of CORSIKA showers [6] with proton and iron primaries was used. Dependences on hadronic interactions were tested by comparing the results of two different models, QGSJetII-03 [7] and EPOS1.99 [8]. The model used for low energy interactions was FLUKA [9].

CORSIKA showers provide the particles at ground level after the shower development in the atmosphere. To have a wide representation of different effects that can be observed in the detection of real showers, the library includes simulations with different atmospheric parametrizations, primary energies ($10^{18.5}$ eV, 10^{19} eV, $10^{19.5}$ eV, 10^{20} eV), and impinging angles ($0^\circ, 12^\circ, 25^\circ, 36^\circ, 45^\circ$).

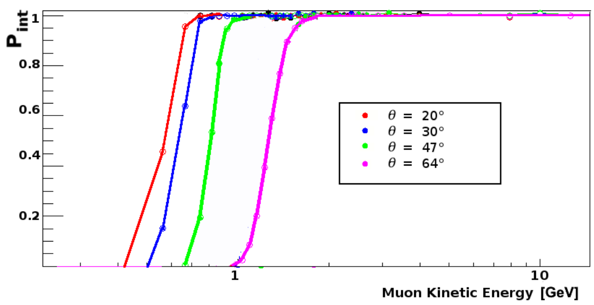

Figure 1: Muon trigger probability due to soil shielding. Different particle energies and particle impinging angles are shown.

Following the construction of the universality model, ground level particles are separated into four components: (a) The purely electromagnetic component, (b) the electromagnetic component coming from muon interactions and muon decay, (c) the electromagnetic component from low-energy hadrons (jet component), and (d) the purely muonic component [2]. For the simulated response of each detector, information on the signal contribution of each of the components is stored. The surface detector signal is the sum of the four components signals. In the particular case of the muon detector, the soil shields nearly all particles belonging to the first three components, signal contributions from these components are negligible (lower than 3%). Only the muonic component outlast. The particles detected underground (without any detector effects) are depicted in Figure 1.

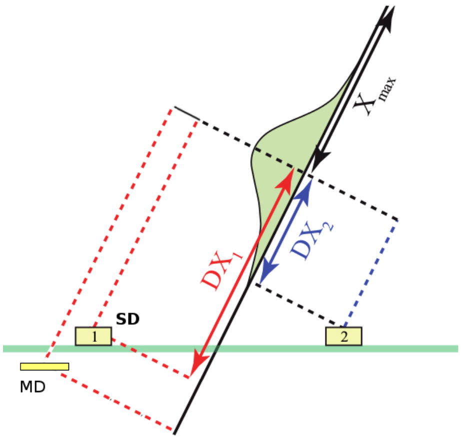

Figure 2: *DX* defined as the integrated density of the atmosphere from X_{max} to the position of the detector projected on the shower axis.

A change in coordinates is needed to derive a universal description: *DX* is defined as a detector's distance to the atmospheric slant depth at which the shower develops the maximum number of particles (X_{max}). Figure 2 depicts this definition. Use of *DX* allows all showers to be described by a universal shape.

The proposed signal model is then the sum of contributions to the total signal from the different components in a detector. As previously mentioned, this parametrization only depends on E, R_μ and *DX* (where *DX* carries the dependence on X_{max} and the geometry of the EAS). If we consider all possible effects due to the atmosphere and the detector response (treated as corrections to the ideal detector signal S_0), we arrive at Equation 2.1.

$$S(E,R_\mu,DX) = \sum_{i=1}^{4} S_0^i(DX,E)\cdot f^i_{\text{mod}}(r \mid \theta,\psi)\cdot f^i_{\text{conv}}(r,DX,\theta,\psi)\cdot f^i_{R_\mu\text{fluct}} \tag{2.1}$$

- $S_0^i(DX,E)$ is the ideal detector signal, without any detector geometry besides an area of 10 m^2 or atmospheric effects.
- *DX* carries the dependence on X_{max} and geometry.
- f^i_{mod} is the conversion factor from shower signal into ideal detector at (θ,ψ).
- f^i_{conv} is the conversion factor to a real detector.
- $f^i_{R_\mu\text{fluct}}$ is a factor that takes into account fluctuations in muon production in the shower and it depends explicitly on each component as follows: $S(\ldots) = \sum\left\{S^{\text{ref}}_{\text{em}}(\ldots) + R_\mu[S^{\text{ref}}_\mu(\ldots) + S^{\text{ref}}_{\text{em}\mu}(\ldots)] + R_\mu^{\alpha(\ldots)} S^{\text{ref}}_{\text{em Had}}(\ldots)\right\}$

Each ideal signal component (S_0^i) detected by the muon counter or the water-Cherenkov detector is described with a general function, Equation 2.2. It was found that each detector can be parametrized by this same function (where only the parameters values differ).

$$S_0^i(DX,E) = S_{\text{ref}}\left(\frac{E}{10^{19}\text{eV}}\right)^\gamma \left(\frac{DX-DX_0}{DX_{\text{ref}}-DX_0}\right)^{\left(\frac{DX_{\text{max}}-DX_0}{\lambda(E)}\right)} exp\left(\frac{DX_{\text{ref}}-DX}{\lambda(E)}\right) \tag{2.2}$$

3. Signal model of the muon counter

The signal detected by a muon counter such as that of the Pierre Auger Observatory [10] was parametrized based on the model description in the previous section. The general procedure is summarized in Figure 3. Equation 2.2 can be rewritten for the special case of the muonic component (including the dependence on R_μ) as in Equation 3.1.

$$S_0^\mu(DX,E,R_\mu) = R_\mu E^\gamma f(DX) \tag{3.1}$$

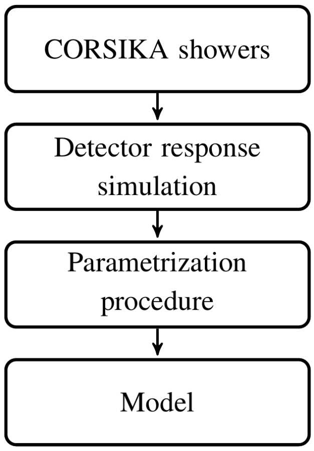

Figure 3: Construction procedure of the signal model.

The estimated γ results in a value of about 1, and hence E and R_μ are strongly correlated. If we only consider the surface detector universality model for the total signal, it is very difficult to come to an unbiased and precise value for both parameters. A direct measurement of the muonic component from the addition of muon counters to the reconstruction procedure compliments the description and facilitates an independent estimation of both parameters with good resolution.

By the end of the procedure outlined in Figure 3, the aim is to have two independent signal models: one for the surface detector and another for the muon detector. Combining all the CORSIKA showers, S_{ref}, γ, DX_{max} and λ were parametrized as a function of the station distance to the core, r, for the special case of the signal detected by a muon counter. These parametrizations complete the description of Equation 2.2. Some examples of the signal of different showers and the model are given in Figure 4.

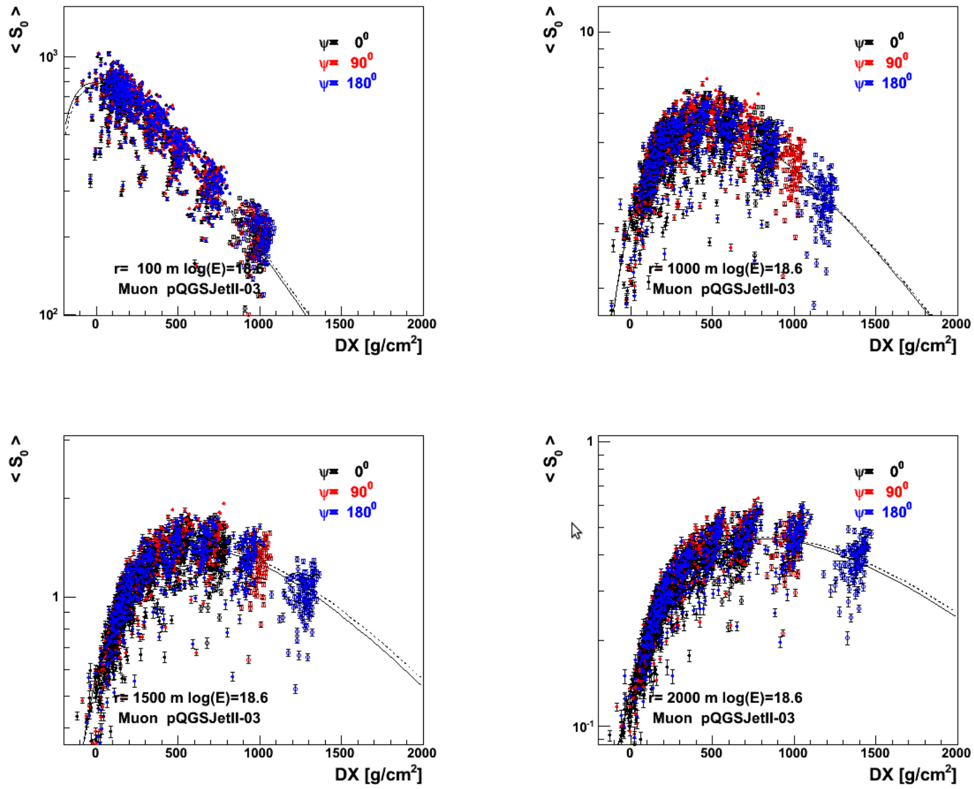

Figure 4: Ideal detector signal as a function of DX. Each bunch corresponds to a different zenith angle of the impinging shower. The colors represent different azimuth angles. Dotted and full lines correspond to the respective models for proton and iron. Due to the small differences, the parameters for the proton showers were used as the parameters of the final model.

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The other atmospheric and geometrical effects were also estimated and included in the description of the model: following Equation 2.1, the ideal signal, S_0, of Figure 4 is multiplied by the corrections to obtain the real signal, S_{Real}.

4. Accuracy of the signal model

To test the accuracy of the model obtained, the signals for each detector in an ideal array were predicted using the model proposed in the previous section and compared to the simulated signal.

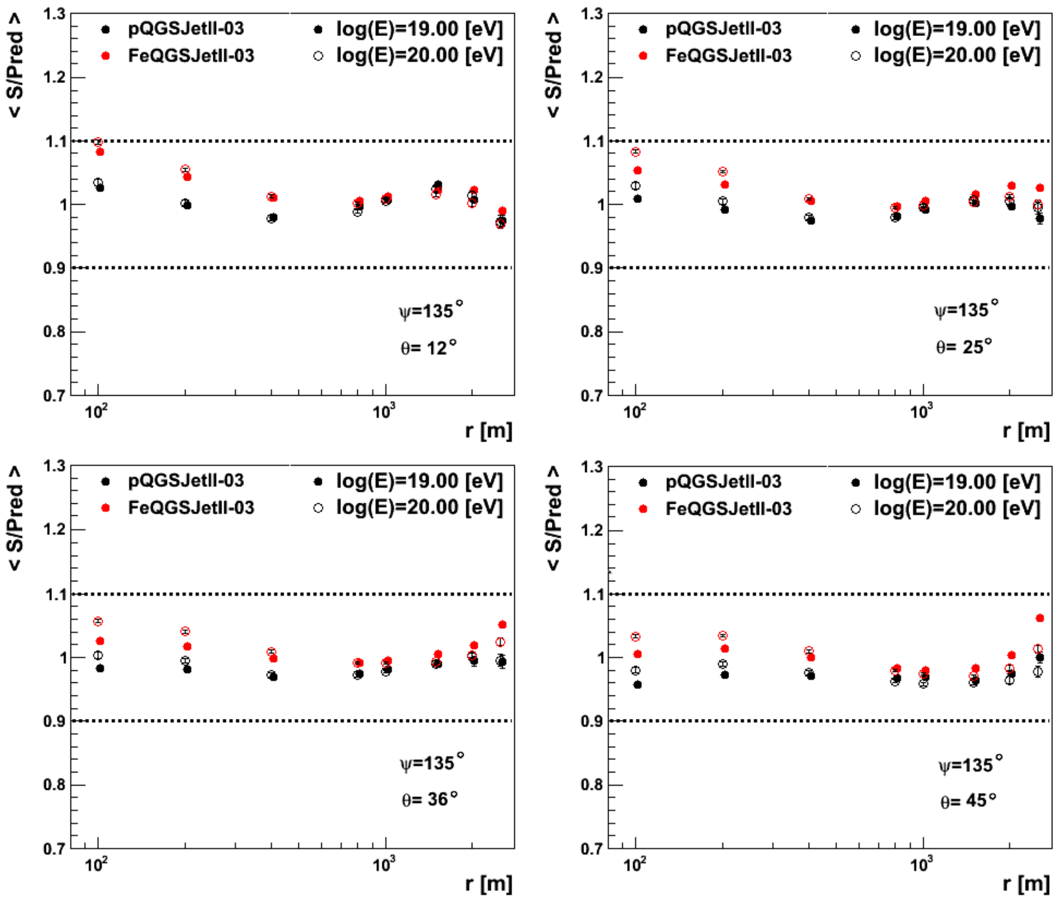

Figure 5: Mean ratio between the real detector signal (S) and the signal predicted by the model (Pred). All the corrections due to atmospheric and geometrical effects are included. In all the examples, the predicted signals do not differ from the real signal, in average, by more than 10%.

Figure 5 shows that in a station-by-station comparison, the predicted signals do not differ from the real signals by more than 10%, and in most cases considerably less. Similar results to those shown in Figure 5 were obtained for the other hadronic interaction model (EPOS-1.99) and for different primary energies and shower geometries. The proposed model appears to yield correct predictions for different hadronic models and primaries, as the universal description claims. This means that a proton and iron are indistinguishable in terms of the employed model (i.e. QGSJet-03 proton model parameters are practically almost the same from the ones that would be obtained for QGSJet-03 iron, EPOS-1.99 proton and iron), within a certain degree of accuracy. They only substantially differ in the general muon content factor R_μ. A similar model was implemented previously to estimate signals in water-Cherenkov detector [2].

5. Results

The universality model presented shows that the signal produced by a muon detector can also be described only by a few parameters: E, R_μ and DX (which carries the geometry and $X_{\max}$ of the shower). If the data of a true observatory is to be reconstructed, the aim would be to combine the parametrizations of both detector types to obtain the shower-level parameters. The shower reconstruction procedure consists of a global likelihood that estimates the shower parameters by using the signals measured by both detectors as an input. To estimate the parameters of interest correctly, some decisions on initial parameter values and which parameters should be free, fixed, and constrained should be made.

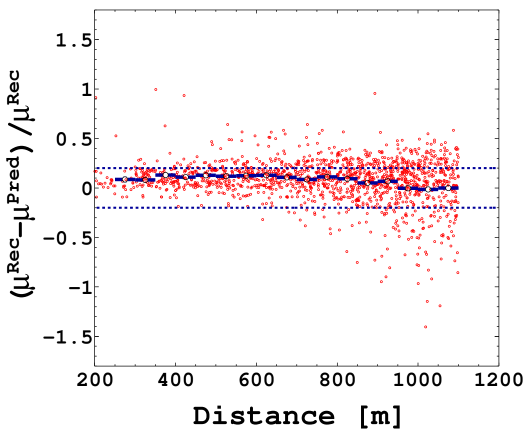

Figure 6: Comparison between reconstructed signals and those predicted by the universality model. Both R_μ and E are reconstructed.

In this work, the derived model was tested with 10 EeV showers with fixed zenith angle of 36°, QGSJetII-04 as the hadronic interaction model, proton and iron primaries. The results then were tested with a different hadronic interaction model from the one used for the universality model construction.

An example of predicted and reconstructed signals is shown in Figure 6. An ideal array with 30 m^2 muon counters and a spacing of 750 m between counters was simulated with the $\overline{\text{Off}}\underline{\text{line}}$ framework [5]. In the reconstruction procedure the core position, geometry and R_μ were free parameters. E was constrained to values within 20% of the initial parameter guess coming from the traditional SD reconstruction. $X_{\max}$ was fixed to the mean value of simulations for the geometry, zenith angle, and hadronic interaction model, but was permited to fluctuate within 20 g/cm^2.

Preliminary results show that the bias in the reconstructed E and R_μ is less than 10%. The resolution on R_μ yields merit factor [1] estimates for mass composition separation of around 2.

[1]Defined as $(< R_\mu^{Pr} > - < R_\mu^{Fe} >)/\sqrt{(\sigma^2_{R_\mu^{Pr}} + \sigma^2_{R_\mu^{Fe}})}$

These results are promising, but we should note that many stations were triggered, given the high energy of the simulated showers.

6. Summary and future work

A model that describes a muon detector signal in the core distance range of 100 to 2000 m and the zenith angle range of 0° to 45° was obtained. Signal estimation close to the needs further studies due to possible saturation problems. The combination of two detector types yields a promising improvement to both E and R_μ of the EAS. An independent procedure facillitating the derivation of a new energy scale is of great value and can be directly compared with the energy estimation of the fluorescence detector of the Pierre Auger Observatory. This energy estimation also does not require a calibration curve, and energy can be reconstructed directly with a nearly 100% duty cycle. Also, R_μ is an estimator of particle composition and is also sensitive to hadronic interaction models, which facilitates comparisons of different interaction models with measured data. A good resolution in the estimation of this parameter can aid in understanding differences in the muonic component of different hadronic interaction models and tendencies in the mass composition of measured data. Furthermore, an accurate measurement of R_μ can also aid in the reduction of systematic errors arising from the missing energy estimation (proportional to the muon content) used in the conversion factor needed by fluorescence experiments to convert the measured calorimetric energy into total energy.

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