Precise determination of muon and electromagnetic shower contents from shower universality property

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Abstract: We present two new aspects of Extensive Air Shower (EAS) development universality allowing to make accurate estimation of muon and electromagnetic (EM) shower contents in two independent ways. In the first case, to get muon (or EM) signal in water Cherenkov detectors it is enough to know the vertical depth of shower maximum and the total signal. In the second case, the EM signal can be calculated from the primary particle energy and the zenith angle. In both cases the parameterizations of muon and EM signals are almost independent on primary particle nature, energy and zenith angle.

Keywords: shower universality, muon signal, electromagnetic signal, Cherenkov water detectors

Introduction

Mass composition of ultra-high-energy cosmic rays (UHECR) can be studied only indirectly with large EAS arrays. The contemporary measurement of longitudinal and lateral shower characteristics in hybrid experiments like the Pierre Auger Observatory [1] provides the possibility to combine several primary mass sensitive EAS parameters (such as depth of shower maximum and muon shower content) to achieve the best primary particle mass discrimination. Unfortunately, the lack of reliable information on hadronic interaction properties at these energies causes large uncertainties in the simulations of EAS characteristics and in turn brings large uncertainties in mass composition analysis results (see e.g. recent review [2]).

In this paper we propose two simple, independent and accurate methods to determine muon and EM shower contents in hybrid experiments and briefly discuss a possible way to test and adjust interaction models properties in a primary mass independent way. We also hope that the proposed EAS-universality-based correction of the interaction models will allow to perform mass composition analysis with the use muon EAS content in less interaction model dependent manner.

The present study is performed making use of around 50000 showers, generated with CORSIKA 6.735 [3]/QGSJET II [4]/Fluka [5] (see [6] for full list of references and more details) and CORSIKA 6.900/EPOS 1.99 [7]/Fluka for E^{-1} spectrum in the energy range $\lg(E/\mathrm{eV}) = 18.5 - 20.0$ and uniformly distributed in $\cos^2\theta$ in zenith angle interval $\theta = 0° - 65°$. EM component thinning was set to 10^{-6}, the observation level was at 870 g/cm^2, geomagnetic field was set to the value of the site of the Auger Observatory in Malargüe. The expected signal S in Cherenkov Auger-like detectors was calculated according to the sampling procedure described in [8, 9] with the use of the same GEANT 4 lookup tables as in [9]. Differently from [9] in this work the muon signal S_μ includes only signal from muons crossing the Cherenkov detector, while signal from EM particles, originating from muon decays, is included in the EM signal.

1 Showers at the same $\mathrm{X}^{\mathrm{v}}_{\mathrm{max}}$

Of all aspects of universality of shower development, we will be interested only in dependence of EM and muon signals on the distance of shower maximum to the ground and on the zenith angle. Let's consider the Auger-like experimental setup [1] and ground-plane signal in water Cherenkov detectors at 1000 meters from the shower core.

Comparing shower characteristics dependence on the vertical depth of shower maximum $X^{\mathrm{v}}_{\mathrm{max}}$ one finds a very interesting property. Clearly, to have the same $X^{\mathrm{v}}_{\mathrm{max}}$ an average proton shower has to be more inclined than the iron shower of the same energy. Therefore, the EM component in the proton shower will attenuate more while reaching the ground from the shower maximum and it turns out

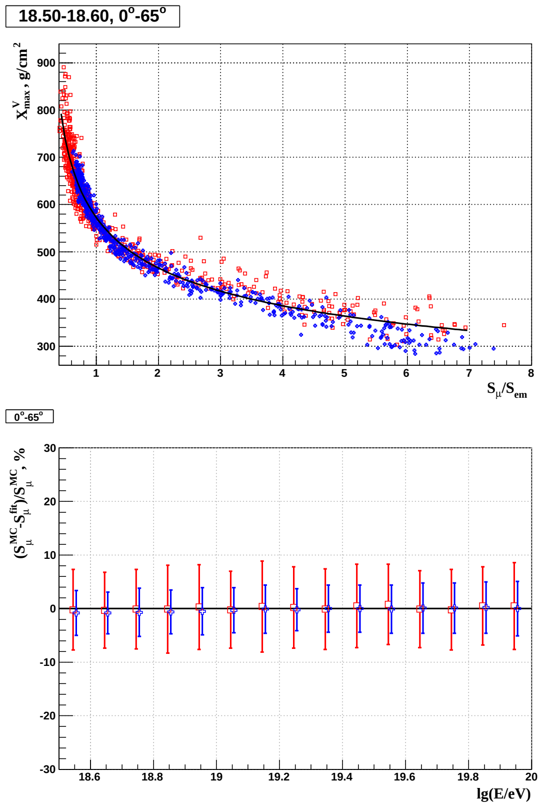


Figure 1: Top: ratio of ground plane signals at 1000 m in water Cherenkov detectors $S_\mu/S_{\rm em}$ vs vertical depth of shower maximum $X^{\rm v}_{\rm max}$ in $10^{18.5}-10^{18.6}$ eV energy range for QGSJET II. Black line is the fit in the form (1). Bottom: means and RMS of distributions of relative difference between MC simulated muon signals $S^{\rm MC}_\mu$ and muon signals derived from the fit (1) $S^{\rm fit}_\mu$, calculated with the unique set of parameters for all energy bins: $A = 538$, $b = -0.25$, $a = -0.22$. Protons — red squares, iron — blue crosses.

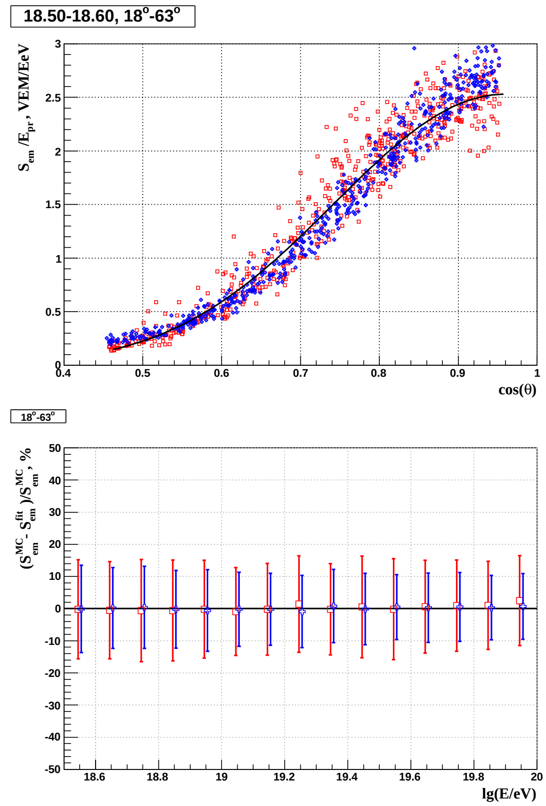


Figure 2: Top: EM ground signals at 1000 m in water Cherenkov detectors vs $\cos(\theta)$ in $10^{18.5}-10^{18.6}$ eV energy range and $\theta = 18°-63°$ zenith angle range for QGSJET II. Black line is the fit in the form (3). Bottom: means and RMS of distributions of relative difference between MC simulated EM signals $S^{\rm MC}_{\rm em}$ and EM signals derived from the fit (3) $S^{\rm fit}_{\rm em}$, calculated with the unique set of parameters for all energy bins: $S^0_{\rm em} = 2.53$, $c_0 = -3$, $c_1 = 0.96$, $\lambda = 0.012$. Protons — red squares, iron — blue crosses.

that $S^{\rm Fe}_{\rm em}/S^{\rm p}_{\rm em}$ ratio becomes almost equal to the $S^{\rm Fe}_\mu/S^{\rm p}_\mu$ one, that allows to state a new shower universality property: the ratio of the muon signal to the EM signal $S_\mu/S_{\rm em}$ is the same for all showers, reaching the maximum at the same vertical depth $X^{\rm v}_{\rm max}$, independently on the primary particle nature, primary energy and incident zenith angle (for the energy and angular ranges considered here). This property is illustrated in Fig. 1, where the dependence of $S_\mu/S_{\rm em}$ on $X^{\rm v}_{\rm max}$ for p and Fe primaries is shown in $\lg(E/{\rm eV}) = 18.5 - 18.6$ energy bin. The functional dependence between $X^{\rm v}_{\rm max}$ and $S_\mu/S_{\rm em}$ turns out to be very simple and quasi-universal for all energies and primaries. The following function

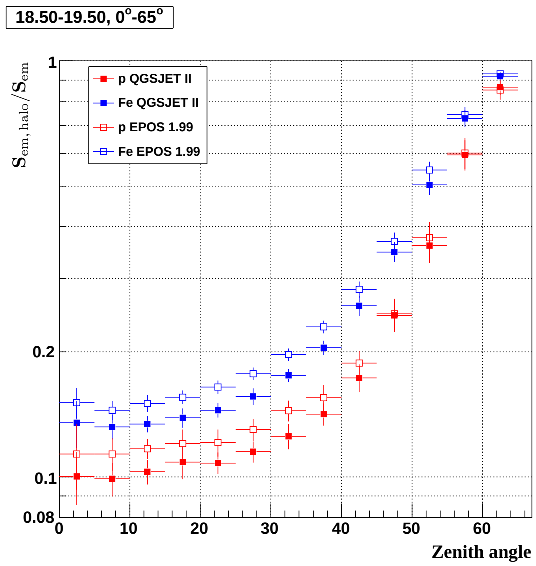
$$X^{\rm v}_{\rm max} = A(S_\mu/S_{\rm em} + a)^b \qquad (1)$$

has been used to fit the data in 15 energy bins $\Delta\lg(E/{\rm eV})$=0.1 and the fit parameters have been found to be stable across the entire energy range. Using the functional dependence of $S_\mu/S_{\rm em}$ on $X^{\rm v}_{\rm max}$ and $S_{1000} = S_{\rm em} + S_\mu$ one easily gets the equation, which allows to obtain the muon signal from vertical depth of maximum and total signal in water Cherenkov detectors:

$$S^{\rm fit}_\mu = \frac{S_{1000}}{1 + 1/((X^{\rm v}_{\rm max}/A)^{1/b} - a)}. \qquad (2)$$

We calculated the difference between the Monte-Carlo (MC) simulated muon signal $S^{\rm MC}_\mu$ and the muon signal obtained from the fit $S^{\rm fit}_\mu$. In Fig. 1 we plot the behaviour of the mean and RMS values of these distributions for various energies, obtained with the unique set of fit parameters $A = 538$, $b = -0.25$ and $a = -0.22$, representing the averages over 15 $\Delta\lg(E/{\rm eV})$=0.1 energy bins. It is seen that the estimates of muon signals are unbiased with less than 1% deviation of the mean reconstructed muon signal from the MC one for all primaries and the RMS values are small: 8% for protons and around 5% for oxygen and iron (though we don't show results for oxygen, we use oxygen showers together with proton and iron ones to perform fits).

In case of EPOS 1.99 the same universality holds and the fit in the form (1) also provides good description of the simulated data, but, as expected, the coefficients of the fit are different from those for QGSJET II.



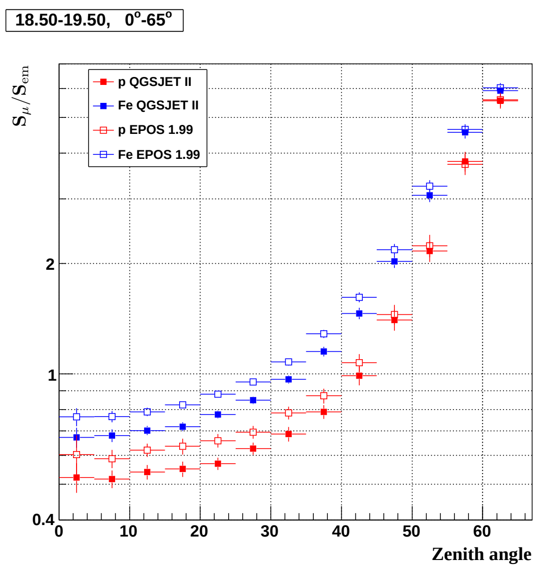


Figure 3: Top: EM muon halo fraction $S_{\rm em,\,halo}$ of total EM signal $S_{\rm em}$ vs zenith angle. Bottom: $S_\mu/S_{\rm em}$ dependence on the zenith angle. $\lg(E/{\rm eV}) = 18.50 - 19.50$.

2 Showers at the same zenith angles

Another universality property follows from the study of showers arriving at the same zenith angles. In this case the average iron shower has to cross larger slant distance from $X_{\rm max}$ to the ground with respect to the average proton shower and this almost equalizes EM signals for both primaries at the observation level in a wide range of zenith angles. For the signal at 1000 meters in the Cherenkov water detectors notable discrepancies between p and Fe EM showers components are observed for nearly vertical showers ($\theta < 18^\circ$, $\cos^2(\theta) > 0.9$) and very inclined ones ($\theta > 63^\circ$, $\cos^2(\theta) < 0.2$). In the first case the path from $X_{\rm max}$ to the ground for p and Fe showers is almost the same. For inclined showers the difference is caused by the EM halo from muon decays and larger number of muons in iron showers brings to a larger EM halo signal.

Looking at the showers at different zenith angles one samples longitudinal showers profiles, for this reason it is natural to try to describe the dependence of the EM signal on $\cos(\theta)$ with Gaisser-Hillas type function, using $\cos(\theta)$ as variable instead of $X_{\rm max}$:

$$\frac{S_{\rm em}(E,\,\theta)}{E}\left[\frac{\rm VEM}{\rm EeV}\right] = S^0_{\rm em}\left(\frac{\cos(\theta)-c_0}{c_1-c_0}\right)^{\alpha}\times$$
$$\times\exp\left(\frac{c_1-\cos(\theta)}{\lambda}\right), \quad (3)$$

where $\alpha = (c_1 - c_0)/\lambda$; $S^0_{\rm em}$ (signal at maximum), c_0, c_1 (cosine of angle at which $S_{\rm em}$=$S^0_{\rm em}$) and λ are fit parameters. The fit parameters $S^0_{\rm em}$ and c_1 change by less than 10% and 3% correspondingly across the entire range of energies (when one makes fits in 15 energy bins $\Delta\lg(E/{\rm eV})$=0.1 from $\lg(E/{\rm eV}) = 18.5$ to $\lg(E/{\rm eV}) = 20.0$), while c_0 changes quite chaotically from 0 to -20 (this causes λ to change also). We have found that fixing c_0 (similarly to [9]) to any negative value within this range, we obtain a good universal fit and λ changes in this case by less than 15%. Finally, we used the following average values (except for c_0 that was fixed to -3) of the coefficients $S^0_{\rm em} = 2.53$, $c_0 = -3$, $c_1 = 0.96$, $\lambda = 0.012$. The results of the fit and the difference between the MC simulated EM signal $S^{\rm MC}_{\rm em}$ and the EM signal obtained from the fit $S^{\rm fit}_{\rm em}$ are shown in Fig. 2. The accuracy of the EM signal reproduction for all energy bins is such that one gets an unbiased estimate of $S_{\rm em}$ with RMS below 15% for proton and 13% for iron showers.

Our calculations demonstrate that the universality of EM signal dependence on zenith angle holds true also in case of EPOS 1.99.

3 $\mathrm{S}_\mu/\mathrm{S}_{\rm em}$ universality in respect to interaction models for $\theta > 45^\circ$

Phenomenologically the angular region $45^\circ - 65^\circ$ is of interest since with increase of the zenith angle the EM component produced mostly in π^0 decays at the initial EAS development stages is largely absorbed in the atmosphere and EM halo from muon decays starts to play a remarkable role (Fig. 3). One expects in this case that the behavior of the $S_\mu/S_{\rm em}$ ratio should become less sensitive to the properties of the interaction models since with increase of the angle it more and more reflects the equilibrium state between muons and EM halo from muons decays and interactions. To illustrate quantitatively this process let us write the $S_\mu/S_{\rm em}$ ratio for QGSJET II as

$$S^{\rm QGS}_\mu/S^{\rm QGS}_{\rm em} = \frac{S^{\rm QGS}_\mu}{S^{\rm QGS}_{\rm em,\,halo} + S^{\rm QGS}_{\rm em,\,pure}},$$

here $S^{\rm QGS}_{\rm em,\,halo}$ is the EM halo signal from muons, $S^{\rm QGS}_{\rm em,\,pure}$ is EM signal from everything else except muons. Then for

EPOS 1.99 one gets

$$S_\mu^{\rm EPOS}/S_{\rm em}^{\rm EPOS} = \frac{\mu S_\mu^{\rm QGS}}{\mu S_{\rm em,\,halo}^{\rm QGS} + \varepsilon S_{\rm em,\,pure}^{\rm QGS}},$$

where $\mu = S_\mu^{\rm EPOS}/S_\mu^{\rm QGS}$ and $\varepsilon = S_{\rm em,\,pure}^{\rm EPOS}/S_{\rm em,\,pure}^{\rm QGS}$ are the scaling factors between muon and EM signals of the models and we have taken into account that $S_{\rm em,\,halo} \propto S_\mu$ and so $\mu = S_{\rm em,\,halo}^{\rm EPOS}/S_{\rm em,\,halo}^{\rm QGS}$. In these notations one gets

$$\frac{S_\mu^{\rm EPOS}/S_{\rm em}^{\rm EPOS}}{S_\mu^{\rm QGS}/S_{\rm em}^{\rm QGS}} = 1 + \frac{\mu - \varepsilon}{\varepsilon + \mu(S_{\rm em,\,halo}^{\rm QGS}/S_{\rm em,\,pure}^{\rm QGS})}. \quad (4)$$

One can see from Eq. (4) that with the increase of the zenith angle and hence of $S_{\rm em,\,halo}^{\rm QGS}/S_{\rm em,\,pure}^{\rm QGS}$ the difference between models in $S_\mu/S_{\rm em}$ is decreasing as shown in the bottom panel of Fig. 3. Let us note that from the approximate equality of $S_\mu/S_{\rm em}$ ratios for different models it follows that for any primary nucleus (p, O, Fe etc.) the following equality holds

$$\frac{S_{1000}^{\rm EPOS}}{S_{1000}^{\rm QGS}} \approx \frac{S_\mu^{\rm EPOS}}{S_\mu^{\rm QGS}} \approx \frac{S_{\rm em}^{\rm EPOS}}{S_{\rm em}^{\rm QGS}}. \quad (5)$$

This, in turn, means that Eq. (2) in this angular range provides an almost model-independent estimate of the muon signal. In fact, since the muon signal scales in the same way as the total signal, if one applies e.g. Eq. (2) with fit parameters for QGSJET II to the data simulated with EPOS 1.99, the total signal of EPOS 1.99 will give correct normalization for the muon signal. The difference between models in $X_{\rm max}^{\rm v}$ and in the functional dependence on $X_{\rm max}^{\rm v}$ will play only a minor role. As it will be demonstrated elsewhere [12] the muon signal for EPOS 1.99 can be retrieved with the use of the QGSJET II fit parameters with accuracy of 3–5%.

Conclusions

We have presented two new EAS universality properties providing two independent ways to access EM and muon shower contents. We have shown that these properties can be described with simple parametrizations which are valid in wide energy and zenith angle ranges, and are independent on the primary particle nature. We believe that these universality properties can be used in hybrid experiments for mass composition studies, for primary and missing energy estimates and for tests of hadronic interaction models. One of the possible strategies lies in the simultaneous application of both universality properties to the data. It is clear that parametrizations (2) and (3) will give consistent estimates of muon and EM shower contents only in case of correct description of the hadronic interaction properties by the particular model. Another interesting strategy can be pursued in hybrid experiments equipped with muon detectors. For zenith angles above 45 degrees where the EM halo plays an important role, this universality property can be used for the determination of the depth of the shower maximum in almost interaction model independent way taking advantage of 100% ground array duty cycle with respect to 10% one of the fluorescence telescopes. On the other hand for angles below 45 degrees the difference in behaviour of $S_\mu/S_{\rm em}$ between models should be large enough so that with simultaneous knowledge of S_μ, $S_{\rm em}$ and $X_{\rm max}$ one could be able to check the predictions of hadronic models quite easily using (1) and comparing e.g. the parameterized $X_{\rm max}$ with the measured one.

Finally, we would like to dwell on the problem of muon excess in the real data compared to predictions of the interaction models [9–11]. Since the muon content of EAS is highly model-dependent and the UHECR mass composition is still unknown, this muon excess can be expressed only in terms of a relative excess with respect to the prediction of a given hadronic interaction model for a given primary like (real signal)/(MC signal for protons). In [12] we show that for the zenith angles above 45 degrees it is possible to get muon shower content from real data in almost interaction model independent way (see application to the data of the Pierre Auger Observatory in [13]). This, in turn, provides us with EM shower content which is weakly sensitive to the mass of the primary particle and hence allows to find the absolute scaling factor (real signal protons)/(MC signal protons). Performing such scaling on the one hand will diminish the difference in predicted muon signals between different interaction models, and on the other hand will open the possibility to use the muon signal for mass composition studies.

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