Extensive Air Shower Universality of Ground Particle Distributions

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Abstract: The number and the energy and angular distributions of particles in extensive air showers depend on the stage of the shower development and the distance to the shower axis. In this work we derive an analytic parameterization of the particle distributions at ground from air shower simulations. Shower particles are classified in four components according to the shower component they belong to and the transverse momentum of the last hadronic interaction of their production. Using this scheme, we will show that the total signal at ground level can be described with universal parametrizations in dependence on the primary energy, position of the shower maximum, and the overall number of muons in the shower. The simulation results are reproduced with an accuracy of 5-10% in the range from 100 to 2000 m from the shower core. The differences between hadronic models and primaries are only due to the different predictions of these quantities. The truncation of the shower development due to the presence of the ground is taken into account and effects due to the geometry of possible surface detectors are outlined.

Keywords: UHECR, shower universality, muons, Pierre Auger Observatory

1 Introduction

The origin of ultra-high energy cosmic rays (UHECR, with energies beyond 1 EeV) still remains a mystery. Experimental results [1] suggest that the UHECR flux is composed predominantly of hadronic primary particles. As charged particles, they suffer deflections in cosmic magnetic fields and do not point back directly to their sources. An indirect search for their origin is necessary instead: the precise measurement of the energy spectrum, an estimation of the mass composition and its evolution with energy, and angular anisotropies are the three main handles on disentangling this almost century-old problem.

Due to the low fluxes at ultra-high energies, the detection of UHECR can only be achieved by measuring extensive air showers (EAS), cascades of secondary particles resulting from the interaction of the primary cosmic rays with the Earth's atmosphere. The measurement of the cosmic ray energy, flux, and mass composition relies on a good understanding of this phenomenon.

It is known that the electromagnetic component of extensive air showers of very high energy ($E \gtrsim 1$ EeV) is characterized by a number of important universality features, see for example [2]. The bulk of electromagnetic particles exhibits an energy spectrum that depends only on shower age and the angular distribution of electrons depends only on their energy. To exploit shower universality in the analysis of data of modern cosmic ray detectors it is necessary to extend the universality concept to the muonic shower component. Using simulations it was found that the longitudinal profile of muons in an air shower has an universal shape, too, with only the normalization and depth of maximum changing from shower to shower. Based on this finding, a parameterization of the signal expected in surface detector stations of the Pierre Auger Observatory had been developed for a distance of 1000 m from the shower core [3].

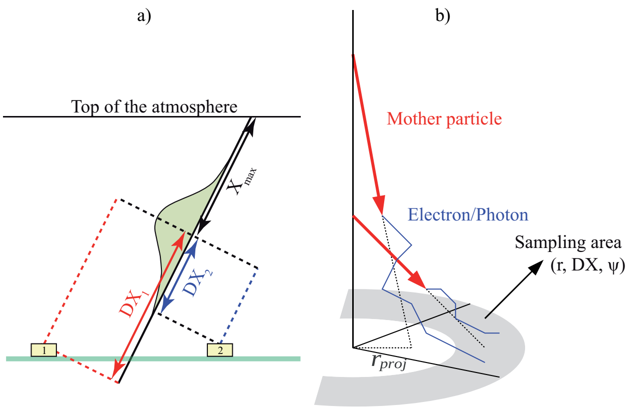

Figure 1: Definition of the distance of a detector station to the shower maximum (left) and sketch to illustrate the definition of an electromagnetic particle from a *jet* (right).

In this paper we shall develop a new universality description of air showers. In contrast to the previous parametrization of universality features we explicitly use the relation between neutral pions (photons) and charged pions

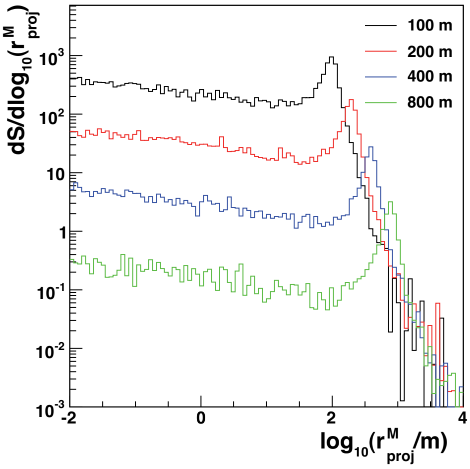

Figure 2: The distribution of r_{proj} for electromagnetic particles falling in sampling areas centered around a distance r_{dist} of 100, 200, 400 and 800 m, respectively. The shower was simulated with the CORSIKA history version. The X_{max} is 1010 g/cm^2, the primary proton, the zenith angle 45° and the energy 10 EeV.

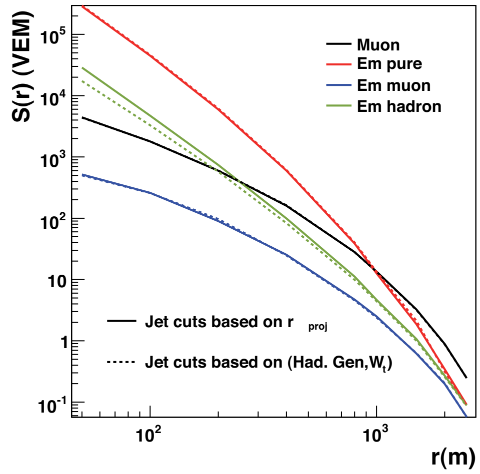

Figure 3: The lateral distribution function for the 4 components for the same shower as in Fig. 2. The different behavior with core distance reflects the different physical origin of the 4 components. The solid line is the outcome of the selection of the jet component based on the cut in r_{proj}. The dashed line indicates the result applying a cut on particle weight and hadronic generation counter instead.

(muons) produced in hadronic interactions at low energy. An extended library of more than 10,000 CORSIKA [4] showers of proton and iron primaries is used to validate the new universality description. A possible dependence on the hadronic interaction models used for these simulations is studied by comparing showers simulated with QGSJetII03 [5] and EPOS1.99 [6]. Hadronic interactions at energies below 100 GeV were simulated with FLUKA [7].

The results presented in this work correspond to detectors with a ψ angle of 90° (detectors at ψ=0°/180° are located below/above the shower axis, see left panel in Fig. 1). The asymmetry of the signal as function of ψ will be discussed elsewhere.

2 Shower components

Simulations show that a significant fraction of the particles arriving at a detector at large distance from the shower core stems from hadronic interactions at low-energy, producing secondary particles at large angles with respect to the shower axis. Introducing the four shower components (a) the muonic component, and (b) the electromagnetic component stemming from muon interactions and muon decay, (c) the purely electromagnetic component, (d) the electromagnetic component from low-energy hadrons (jet component), we find a much more robust universality parameterization of showers.

The newly introduced component d (*jets*) refers to electromagnetic particles for which the spatial distribution at ground is determined by the momentum of the mother particle at the last hadronic interaction as illustrated in Fig. 1. The history version of CORSIKA v.6980 [8] has been used for this purpose. Each particle arriving at ground level is saved together with the information of the *mother* and *grandmother* particle at the last hadronic interaction. The direction of the *mother* particle at the last interaction point is extrapolated to ground level where the distance to the shower core, r_{proj}, of the impact position is calculated. All particles in a sampling area at a given core distance, r_{dist}, are taken to calculate the distribution of r_{proj}. In Fig. 2 the results for 4 different sampling areas are displayed. A clear peak is seen in the distribution of r_{proj} close to a distance of r_{dist}. This peak can only be caused by sub-showers for which the lateral displacement of shower particles at ground level is dominated by the transverse momentum of the particle that initiated the sub-shower. The distributions for different core distances cut off at the core distance of the sampling area (the shower particles diffuse outwards). The ratio between the peak and the plateau of the distribution before the peak increases with core distance, showing the increasing importance of the *jet* component with increasing core distance. An electromagnetic particle is considered to originate from a *jet*, if $\log_{10} r_{\text{proj}} > \log_{10} r_{\text{dist}} - 0.05$.

Making use of an existing large shower library that has been simulated without the history flag of CORSIKA, the jet component has to be inferred by indirect means to generalize the previous concept since the information on the mother particle is not available in this library. The particle weights and the weight limits – differing for different particles species – in combination with the tally of hadronic generations act as an effective measure to discriminate the jet contribution from other components.

As an example, the signal of the four shower components is shown in Fig. 3 for one shower simulated with the history option. The solid (dashed) lines correspond to the cuts

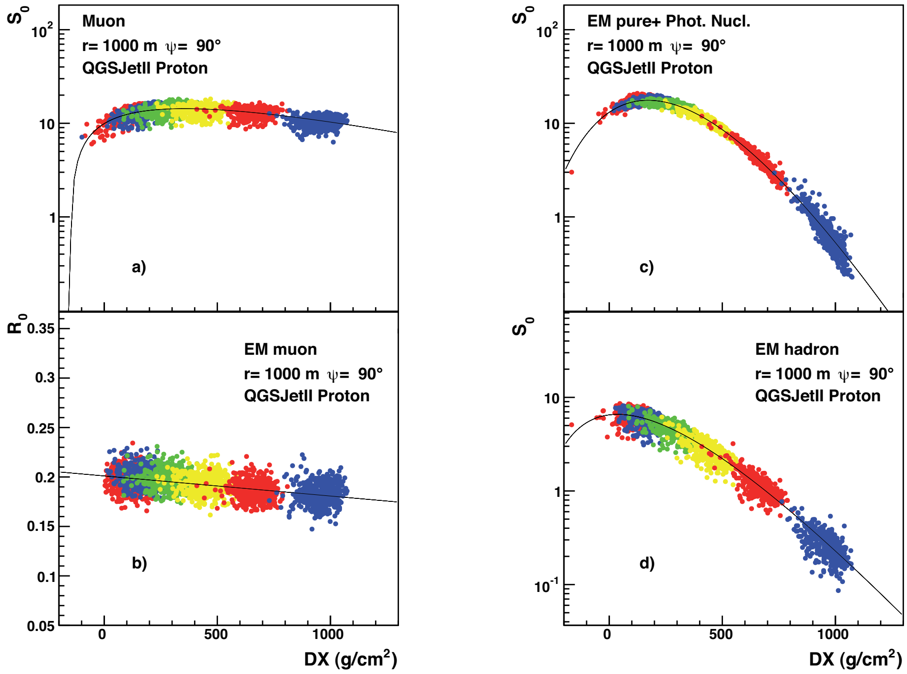

Figure 4: The signal of the different components as a function of DX at r =1000 m. The different colors corresponds to different zenith angles (12, 25, 36, 45, 53, and 60°). The signals at different energies have been normalized to 10 EeV. The lines are the result of the fits.

based on $r_{\rm proj}$ and hadronic generation/weight, respectively. Differences at small core distances for the electromagnetic component from hadron *jets* between the two cuts are apparent. They are most likely because of the $r_{\rm proj}$ cut, where we did not subtract the background appropriately in Fig. 2. The fall-off of the jet component reveals a different radial dependence wrt. the purely em. component signaling a violation of the shower universality reported in [3].

3 Universality parametrization

Based on this extended universality concept we have developed a parametrization of the signal expected in the Auger surface detector stations in the lateral distance range from 100 to 2000 m.

Fig. 4 shows the dependence of $S_{0,i}$ on the distance to the shower maximum DX (see Fig. 1 (left) and [3] for details on the definition of DX) for each of the components considered in this work. $S_{0,i}$ is the signal of the *i*th component in a detector station with a projected area of 10 m^2 regardless the incoming direction of the shower particles and a detector response of an Auger detector in the vertical direction. This definition has been adopted as an intermediate step for calculating the signals in an Auger detector to treat the geometrical asymmetries due to the detector geometry separately. Different energies were rescaled to E =10 EeV for all components except the electromagnetic component stemming from muon interactions and muon decay. This component is shown as a ratio relative to the muonic signal. No energy dependence of the ratio has been observed.

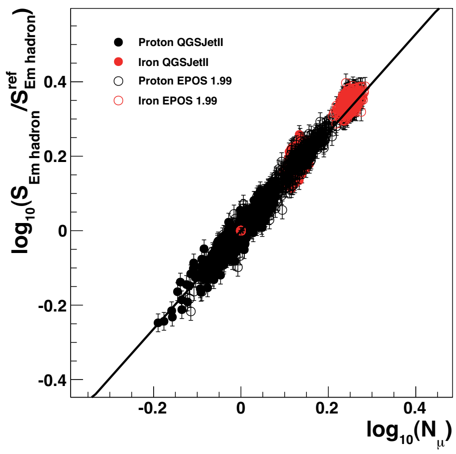

Figure 5: The correlation between N_μ and $S_{0,\rm em_{had}}/S^{\rm ref}_{0,\rm em_{had}}$ for showers at 10 EeV and at 1000 m from the shower core.

The core distance is 1000 m. Similar results are obtained for core distances between 100 and 2500 m.

The individual shower components have been parameterized for proton primaries using the model QGSJetII. The signal $S(r, DX, E)$ in an Auger detector is then given by (the arguments (r, DX, E) are omitted further on):

$$S(r, DX, E) = N_\mu S^{\rm ref}_{0,\mu}(f_\mu + R^{\rm ref}_{0,\rm em_\mu} f_{\rm em_\mu}) \\ + N_\mu^{\gamma_h(r,E)} S^{\rm ref}_{0,\rm em_{had}} f_{\rm em_{had}} + S^{\rm ref}_{0,\rm em} f_{\rm em}, \quad (1)$$

where *ref* is used to indicate that this parameterization is relative to the mean for the reference primary and model. f_μ, $f_{\rm em_{had}}$, $f_{\rm em_\mu}$ and $f_{\rm em}$ are the factors needed to convert $S_{0,i}$ into the expected signal in an Auger detector sta-

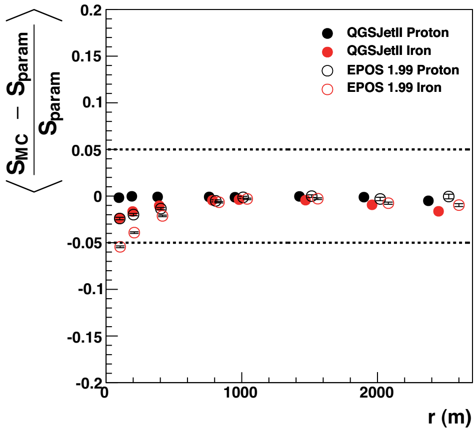

Figure 6: The average value of the residuals as a function of core distance for zenith angles smaller than 50° and for an energy of 10 EeV. All the components were added together.

tion. These factors are different for each of the components due to the different angular distributions of the corresponding particles, and they depend not only on (DX, r) but also on θ and ψ. N_μ is defined as an effective muon number $N_\mu = S_{0,\mu}/S_{0,\mu}^{\rm ref}$, that depends on the primary particle and hadronic model considered. The fluctuations of the electromagnetic component due to hadron *jets* are parameterized employing the intrinsic correlation between the production of neutral and charged pions in low-energy interactions. Fig. 5 shows this correlation between N_μ and $S_{0,{\rm em_{had}}}/S_{0,{\rm em_{had}}}^{\rm ref}$ for showers at 10 EeV at 1000 m from the shower core. The zenith angle range used was 0 to 50°. The fit of $\gamma_h(r, E)$ in Fig. 5 was done using only the reference model (proton QGSJetII). The fact that other models/primaries lie along this line is an empirical finding with interesting consequences: in terms of the universality parametrization, an iron shower is not distinguishable from a fluctuation of a proton shower.

In Fig. 6 the average value of the difference between the parametrization, based on Eq. (1), and the simulation result is shown as a function of core distance for different models and primary particles. Showers with different zenith angles were combined for each core distance. The average values of the residuals do not depend on zenith angle (in the range 0 to 60° and within 5%). The results correspond to an energy of 10 EeV. Similar results are obtained for different energies. As a consequence the only parameters required to predict the detector signal with an accuracy of 5% are $X_{\rm max}$ and N_μ in the core distance range from 100 to 2000 m.

4 Discussion and outlook

An analytical description of the surface detector signal in the core distance range from 100 to 2000 m and the zenith angle range 0 to 60° is possible.

The introduction of the electromagnetic component from hadron *jets* and its correlation with N_μ condenses the primary and model dependences on one single parameter (N_μ). The measurement of this quantity is of direct relevance in the quest to find the origin of cosmic rays at the highest energies. Together with the position of the shower maximum, it will help to break the intrinsic degeneracy between hadronic models and chemical composition.

In [3], the electromagnetic component from hadron *jets* was included in the pure electromagnetic signal introducing an indirect dependence on N_μ of this component. The systematics were estimated using different primaries and two hadronic models with similar muon production. Using Eq. (1) will reduce the systematic uncertainties of measuring N_μ with the methods developed in [3].

The measurement of N_μ will also reduce the systematics in the conversion factor needed in fluorescence experiments to convert the measured calorimetric energy into total energy (the so called *missing* energy is proportional to the muon production in the shower).

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