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An Universal Description of the Particle Flux Distributions in Extended Air Showers

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It is shown that the electromagnetic and muonic fluxes in extended air showers (EAS) can be described using a simple model incorporating attenuation and geometrical dispersion. The model uses a reduced set of parameters including the primary energy E, the position of shower maximum X_{max} relative to the ground, and a muon flux normalization N_μ. To a good approximation, this set of three physical parameters is sufficient to predict the variability of the particle fluxes due to systematic differences between different models of composition and hadronic interactions, and due to statistical event-by-event differences in shower development. Measurements of these three physical observables are therefore unbiased and very nearly model-independent, in contrast with standard measurement techniques. The theoretical problem of determining primary composition is thus deconvolved from the measurement procedure, and may be approached in a subsequent analysis of the measured distributions of (E, X_{max}, N_μ).

1. Introduction

When analyzing EAS data collected by surface detector (SD) arrays, Monte Carlo simulations are often needed to extract information about the primary cosmic ray from the ground level particle fluxes. Because of uncertainties due to the modelling of primary composition and hadronic interactions, the interpretation of the data is somewhat ambiguous and the systematic uncertainties in the analyses are difficult to estimate. By studying simulations performed with AIRES [1] using various combinations of primary composition and hadronic interaction model, we find that all of the model-dependent effects can be parameterized to a good approximation as functions of the position of shower maximum X_{max}, and a muon flux normalization N_μ. Different simulations give systematically different predictions for the mean values and shower-to-shower statistical fluctuations in these two quantities. One can therefore gain information concerning primary composition and interactions by measuring X_{max} and N_μ via the spatial and temporal structure of the fluxes observed in SD arrays.

For example, at ground level the shower can be approximated as a superposition of an electromagnetic (EM) shower composed of $e^+/e^-/\gamma$; and of a muonic shower resulting from the decay of charged pions from a hadronic component of the original shower. As a shower evolves, the flux at any fixed core distance grows due to transverse diffusion of the particles near the core but decreases due to ionization loss. At large traversal distances, the ionization loss is dominant, and attenuates the EM shower much more than the muonic shower due to the large number of particles produced in the EM cascade. The ratio of the fluxes is therefore dependent on both the core distance R of the detector and on the position of the shower relative to the ground, a quantity conveniently parameterized using X_{max}. It is also obviously directly dependent on N_μ.

Furthermore, because of radiative scattering, the EM shower front is delayed in time relative to the muonic shower front. As a result, the muonic flux peaks at earlier times than the EM flux. For the same reason, the spread of the arrival times of the particles is also distinct for EM particles and muons, as the latter ones follow more direct paths from their production sites. This phenomenon can be observed in the time structure of the signals which then provides more information about X_{max} and N_μ. Asymmetries in both the signal level and in the time structure also arise in inclined showers. Finally, the time of arrival of the signals can be analyzed to infer a radius of curvature of the shower front which is also related to X_{max}. By parameterizing the particle flux distributions at any observation position and time in terms of (E, X_{max}, N_μ), one can predict the dependence of any ground observable as a function of these parameters. Measurements of these ground observables can therefore be used to constrain these parameters, and to gain information about the cosmic ray primary composition and hadronic interactions [2].

2. The Universal Flux Functions

For this study we use AIRES 2.6.0 simulations, including a shower library consisting of 25,000 showers (generated at Fermilab by Sergio Sciutto) with thinning 10^{-6} and thinning weight 0.15. The ground level is defined as the altitude of the Pierre Auger Observatory in Malargue, with a vertical atmospheric depth of 875g/cm^2. The showers are generated using discrete values of log(E/EeV) = $\{18.0,18.5,19.0,19.5,20.0,20.5\}$, zenith angle θ= $\{0,25,36,45,53,60,66,72,78,84\}$ and azimuthal angle. The showers are simulated with either proton or iron primaries, and with either the SIBYLL 2.1 or QGSJET01 interaction model.

To investigate the evolution of the particle flux as the shower front traverses the atmosphere, we define D_G as the slant depth measured along the shower axis between the position of X_{max} and the detection position on the ground. D_G serves as a convenient age parameter for the shower development. In order to facilitate comparisons between showers at different zenith angles θ, we define the particle fluxes as fluxes through planes (defined locally near each detection position) transverse to the shower axis. To construct the transverse plane fluxes from the ground plane fluxes reported by AIRES, each particle record must be weighted by an acceptance correction factor $\cos\theta \cdot (\hat{p}\cdot\hat{a}/\hat{p}\cdot\hat{v})$ to account for the relative size and orientation of the collection areas in the two planes. The weighted particle counts are then divided by the accumulation area in the transverse plane to obtain the fluxes. $\hat{p}$, $\hat{a}$, and $\hat{v}$ are unit vectors along the particle direction, the downward shower axis, and the downward vertical direction, respectively.

In figure 1, the EM and muon particle number fluxes at a core distance of R=1.1km are plotted versus D_G for four combinations of primary and model. Each plot is comprised of a set of discrete bands, each one corresponding to a fixed zenith angle θ (larger θ correspond to larger D_G). The horizontal dispersion of each band is caused by shower-to-shower fluctuations in X_{max}. The vertical dispersion of the EM flux is caused by poisson fluctuations of the particle fluxes and, in the case of the muon flux, by the combination of poisson fluctuations and fluctuations in N_μ. The simulations all fall along a common curve in the case of the EM flux. Only small differences can be seen, mainly caused by the contribution of muon decay to the EM particle fluxes. This coincidence is perhaps expected since approximately 90% of the shower energy is deposited into the EM component, regardless of the model chosen, and the EM component attenuates predictably with depth.

This coincidence is perhaps expected since approximately 90% of the shower energy is deposited into the EM component, regardless of the model chosen, and the EM component attenuates predictably with depth. It is remarkable that the 'universal' curve is well described by a Gaisser-Hillas (GH) function, that is: the density at a remote distance follows precisely the evolution of the core. The GH shape peaks at about 150-200g/cm^2 when the growth of the flux due to transverse diffusion from the shower core is balanced by the loss due to ionization. The slight mismatches of the slopes of each constant θ band are found to be due to the geometric effect of screening of the particle flux by the earth. i.e. For more inclined showers, a larger fraction of the particle flux at ground with $\hat{p}\cdot\hat{a} > 0$ becomes upward going with $\hat{p}\cdot\hat{v} < 0$, and is hence blocked by the earth.

The muon particle number flux also seems to have a universal shape (which looks similar to a GH function but obviously arises from different underlying physics.) The main difference between simulations with different primary and interaction model assumptions is the overall normalization of the flux. The relative normalization is found to be common to the fluxes at all R, and hence only a single normalization factor N_μ is necessary, and can be defined in an arbitrary way. Therefore, a parameterization of the differences in the simulation predictions in terms of $X_{max}(D_G,\vec{x}_{det})$ and N_μ seems to be appropriate. For ease of comparison, N_μ may be measured in units of the muon flux predicted by some arbitrarily chosen simulation, and can then be interpreted as a ratio of fluxes. Alternatively, it may be measured relative to the normalization of the universal EM flux function and interpreted as the 'muon richness' of the shower.

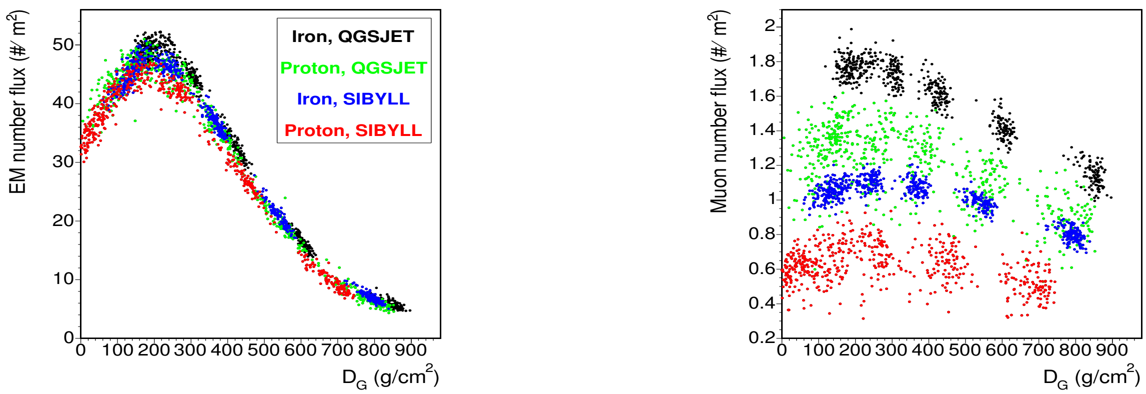

Figure 1. The EM and muon particle number flux plotted vs D_G for 4 combinations of primary particle and interaction model. The data are taken at a core distance R=1.1km from simulations with E=10EeV.

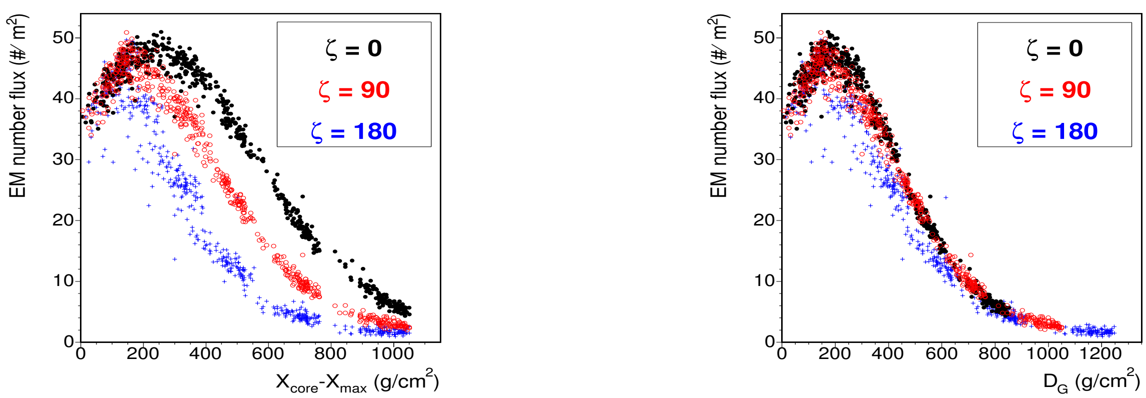

Figure 2. (Left) The EM particle number flux at 3 values of azimuthal angle ζ, plotted versus the slant depth between X_{max} and X_{core}. The data are from simulations of 10EeV protons with QGSJET. (Right) The same, plotted versus D_G.

Signals measured at fixed core distance from inclined showers are also predicted to exhibit an azimuthal asymmetry about the core position. This asymmetry is partially due to the geometric acceptance of the detectors, and partially due to shower development because for inclined showers, D_G varies with azimuthal angle. One may measure in the transverse plane the azimuthal angle ζ from the 'younger' side of the shower. Particles emitted from a fixed point along the shower axis must travel a longer distance to reach a detector at ζ=180 than to reach a detector at ζ=0. In figure 2(left), the EM number fluxes at R=1.1km for ζ=0,90,180 are plotted versus the slant depth between X_{max} and the core position of the shower on the ground. In figure 2(right), the same quantities are plotted versus D_G of the detection position. The asymmetry in the first plot mostly disappears after correcting for the different tranversal distances. The slight residual discrepancies are again due to the geometric earth-screening effect. Because the fluxes are symmetrically defined here in the transverse plane, an additional contribution to the asymmetry due to the geometric acceptance of non-spherical detectors is not exhibited. For real-world detectors, large acceptance corrections may be needed because the distribution of particle incidence angles on the detectors are very different for different values of ζ.

The particle number flux distributions at any detector position can be expressed as functions of D_G which is a function of X_{max}. The normalization of each function is as usual approximately linear in E, and/or N_μ. The fluxes can also be binned in time t, measured with respect to a planar shower front traveling at the speed of light, and expressed again as functions of D_G in each time bin. With such a parameterization, the mean number fluxes of EM particles and muons can be predicted at any ground position from simple universal functions $F^{EM,\mu}[E, X_{max}, N_{mu}](\vec{x}_{det}, t)$ where $\vec{x}_{det}$ is measured relative to the shower geometry. With the approximation that there is no correlated substructure in the shower, the fluctuations in the particle counts measured at each detector position are considered to be independent and Poissonian. These functions F may be used to model the signals in thin scintillation detectors which mainly measure the particle number flux. However, to correct for the geometric acceptance of the detectors as well as for the earth-screening effect, one must also model the angular distribution of the shower particles about the shower axis, as a function of D_G. This can also be accomplished by parameterizing the attenuation losses as a function of this angle. To generalize this method for an arbitrary detector type, one may model the detector response as a function of a particle's type, energy and trajectory to form the corresponding signal flux functions $S^{EM,\mu}$.

3. Conclusions

We have shown that the composition/interaction model dependence of the predicted shower signal fluxes at any detection position relative to the shower geometry can be parameterized by universal functions depending on (E, X_{max}, N_μ). These universal functions may be used to predict the dependence on these parameters of various surface detector observables such as signal asymmetries, signal risetime, and shower front curvature. By inferring the values of (E, X_{max}, N_μ) from measurement of the various observables, one can make stringent tests of models of primary composition and hadronic interactions. An example of a procedure to perform simultaneous event-by-event measurements of these parameters, utilizing the universal flux functions is described elsewhere[3].

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