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A New Technique to Measure Cosmic Ray Energy and Composition Via (2+1)d Lateral Distribution Function Fits to Surface Detector Array Data

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The concept of a one-dimensional lateral distribution function is extended to a set of (2+1)d functions which describe the spatial and temporal distributions of the muonic and electromagnetic components of extended air showers. By design, these functions incorporate the curvature and time structure of the shower front as well as the asymmetries in particle density and in time structure expected in inclined showers. These observables are sensitive to the mass of the primary cosmic ray and to the details of the hadronic interactions inducing the air shower. The (2+1)d functions smoothly interpolate between the values of X_{max} and muon flux predicted by various simulations performed with different assumptions of primary composition and interaction model. A maximum likelihood fit to surface detector array data can then give simultaneous event-by-event measurements of the shower energy, X_{max}, and the muon content, from which the primary composition may subsequently be inferred. The methods outlined are applicable to a large number of existing and future shower detector arrays covering a range of energies.

1. Introduction

It was argued in [1] and references therein that the extended air shower particle fluxes at any observation position can be predicted by a set of 'universal' functions which describe the fluxes independently of any assumptions of primary composition or interaction model. The free parameters of these functions are the primary energy E which determines the overall flux normalization, the position of shower maximum X_{max} which determines the state of evolution of the particle fluxes at ground level, and an independent muon flux normalization N_μ. With these universal functions, the problem of determining primary composition is reduced to the experimental task of making model-independent measurements of the distributions of the physically well-defined observables (E, X_{max}, N_μ). The possibly model-dependent process of inferring the primary composition can then be deferred to a subsequent independent analysis of these unbiased distributions.

In this paper, we propose a specific method for making such measurements of (E, X_{max}, N_μ) using surface detector data, by fitting the universal functions to the measured flux signals. In contrast with the standard method of compressing the measured ground-level signal information into a one-dimensional lateral distribution function (LDF) thus causing (E, X_{max}, N_μ) to be largely degenerate and hence not separately observable, we use the full (2+1)-dimensional signal information which includes information from the time structure of the shower front as well as the spatial and temporal asymmetries in the signals expected in inclined showers. In the following, we illustrate the procedure with the specific example of the cylindrical water Cherenkov surface detectors of the Pierre Auger Observatory. However, the technique can be easily adapted to any other kind of detector technology and array configuration.

At ground level, a shower can be approximated as a superposition of an electromagnetic (EM) shower composed of $e^{\pm}/\gamma$; and of a muonic shower resulting from the decay of charged pions from a hadronic component of the original shower. The first step in the analysis is to create a set of universal functions for each particle type which predict the signal level and its fluctuations at each detector position. To model the signal flux, we need a fast simulation (such as a lookup table) of the detector response as a function of the particle type, energy, trajectory, and detector entry point. For our simplified example, we assume that the Auger tanks yield a signal proportional to the energy of EM particles. We also assume that muons give an average signal proportional to their ionization energy deposit of ∼240 MeV. Note that because the typical energy of EM particles is $<$10MeV, the muon signals are greatly amplified with respect to the EM signals and can thus make large contributions to the time structure of the measured signals. For simplicity, we assume that the fluctuations in the signal level are given by only the Poisson fluctuations of the mean particle number seen by each detector. In principle, the fluctuations from all sources can also be modelled and parameterized.

We therefore create functions for the the mean signal fluxes $S^{EM,\mu}[E, X_{max}, N_\mu](\vec{x}_{det}, t)$, and the corresponding mean number fluxes $F^{EM,\mu}$ with which to estimate the signal fluctuations. To create the flux functions, we use an AIRES 2.6.0 shower library generated at Fermilab by Sergio Sciutto and described in [1]. For each ground particle record in each simulation file, we generate the detector response and make histograms of the number count and the signal in bins of azimuthal angle ζ, core distance R, and time t, for various discrete values of primary energy, type, hadronic model, and zenith angle θ. ζ is measured in the transverse plane from the younger side of inclined showers, and t is measured as a time delay from a planar shower front travelling at the speed of light. The intervals in R and ζ are chosen such that the spatial bins are much larger than the size of the detectors, but still small on the scale of changes in the shower LDF. Thus, the loss of statistics from the shower thinning procedure may be partially recovered [2]. The fluxes are normalized such that when multiplied by the top surface area A_{det} of the detectors, they yield the mean signal and particle number counts in the detector. By constructing these distributions separately in different regions of R and ζ for different values of the shower zenith angle θ, we implicitly include the geometric effects of detector acceptance and earth-screening discussed in [1]. (However, for clarity in the following plots, we choose to mask the geometric effects by plotting the fluxes through local planes transverse to the shower axis.)

2. The Signal Fluxes

In figure 1(left), the EM particle number flux is plotted versus the age parameter D_G which is defined as the slant depth between X_{max} and the observation position, as measured along the shower axis. Each plot is comprised of a set of discrete bands, each band corresponding to the shower-to-shower fluctuations in X_{max} at fixed zenith angle θ. The bands for different choices of primary and model do not precisely overlap because of systematic differences in the mean value of X_{max} predicted by each choice of simulation. However, the simulations all fall along a common Gaisser-Hillas curve in the case of the EM flux. In figure 1(right), the EM number flux is plotted versus both time and D_G. In any of the 50ns time bins, the flux also follows a GH distribution in D_G. These plots illustrate that the longitudinal profile of the EM flux in an EAS has a GH shape, bin-by-bin in the transverse dimensions, and bin-by-bin in time.

In figure 2(left), the corresponding plot is shown for the muon number flux for Proton/QGSJET01 simulations. While both the EM and muon fluxes scale approximately linearly with E, the muon number flux also scales with the mean N_μ predicted by a specific simulation. Otherwise the shape of this function is also universal. The corresponding muon signal flux plot would have a similar shape with a conversion factor of ∼240MeV/muon. In figure 2(right), the EM signal flux plot is shown. Note that there is a large contribution to the EM energy from the muon decay halo which becomes visible at large D_G when the EM cascade signal is attenuated. EM particles created as products of muons decaying close to the detectors have much larger energies than typical particles from the EM cascade. They therefore enter the detectors in time with the muonic shower front, and yield large signals comparable to the muonic signal level. Since these signals are associated with the muonic shower normalization, they should in principle be removed from the EM signal flux function and added to the

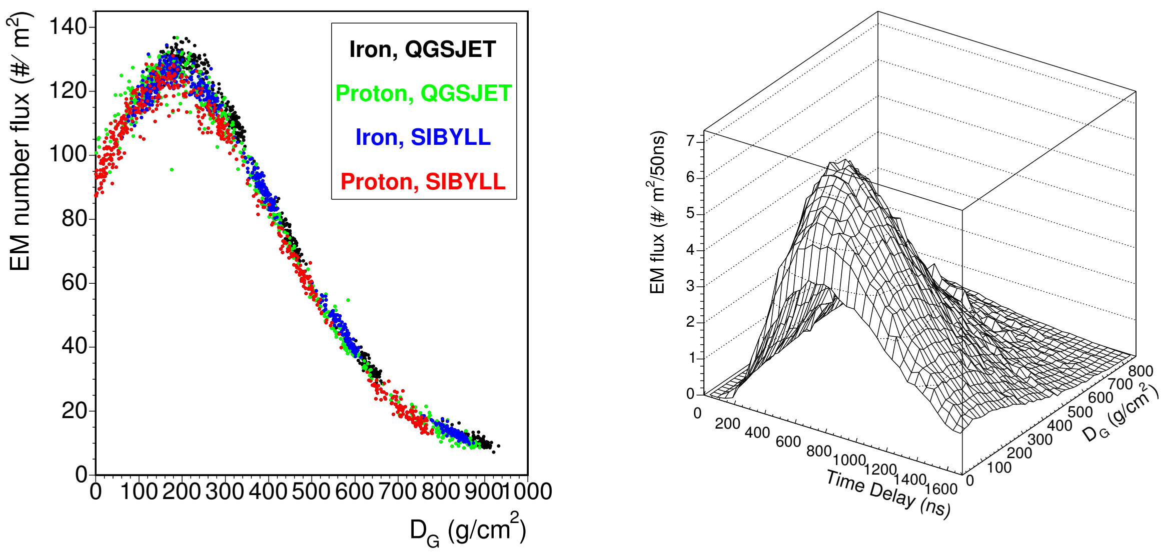

Figure 1. (Left) The EM and particle number flux plotted vs D_G for 4 combinations of primary particle and interaction model. The data are taken at a core distance R=900m and $\zeta = 0$ from simulations with E=10EeV. (Right) The same EM particle number flux in 50ns time bins, plotted versus D_G for the proton/QGSJET01 simulations.

muon signal flux when measuring N_μ. It is found that subtracting ~100MeV/muon bin-by-bin in time from the EM energy distribution provides a reasonable model- and primary energy-independent correction.

Some features of the signal fluxes are evident from the plots shown in figures 1 and 2. First, the muonic flux peaks at earlier times than the EM flux which is delayed by radiative scattering. Furthermore, the EM flux attenuates with D_G due to particle loss via ionization. The ratio of the early- to the late-arriving signal therefore contains information about both N_μ and X_{max}. The shower front curvature which can be seen from the time delay of the signal front as a function of D_G also gives information about X_{max}. Finally, because detectors at different azimuthal angles ζ correspond to different traversal distances D_G, the flux distributions predict an enhancement or attenuation of the EM signal flux as a function of ζ. The resulting asymmetries in both the overall signal level, and in the time structure of the signals give information about both X_{max} and N_μ.

The functions $F^{EM,\mu}$ and $S^{EM,\mu}$ are constructed from a set of distributions like those in figures 1 and 2 made at many values of R and ζ, with all geometric corrections included. The functions are defined by interpolation between fluxes tabulated at discrete values of E, $D_G(R, X_{max})$ and t as well as between discrete values of R, $\cos\zeta$ and $\cos\theta$ in order to model the geometric acceptance and earth-shielding effects. Finally, F^μ and S^μ are assumed to be linearly dependent on the normalization parameter N_μ. By fitting a likelihood function constructed with $F^{EM,\mu}$ and $S^{EM,\mu}$ to the data, one extracts by construction all of the available signal information in order to make a simultaneous measurement of the parameters (E, X_{max}, N_μ). To construct the likelihood function L, note that the probability to obtain the signal D_i in the ith time bin in some detector is

$$P\,(D_i) = \sum_{j=0}^{\frac{D_i}{\langle S^\mu\rangle_i}} \text{Poisson}(j, A_{det} \times N_\mu \times F_i^\mu) \times \text{Poisson}\left(\frac{D_i - j \times \langle S^\mu\rangle_i}{\langle S^{EM}\rangle_i}, A_{det} \times F_i^{EM}\right)$$

In this equation, $\langle S^{EM,\mu}\rangle_i = S_i^{EM,\mu}/F_i^{EM,\mu}$ is the average signal per particle in the ith time bin. All of the functions S and F are evaluated at the detector position relative to the postulated shower geometry.

Poisson(a,b) denotes the probability of obtaining a particle count a from a Poisson distribution with mean value b. Each individual term in the sum is the joint probability of observing a signal comprised of j muons with the remainder of the signal coming from EM particles. We therefore sum over all possible ways to obtain the signal D_i. The total likelihood for obtaining the ensemble of signals from time bins at every detector position may then be defined as the product $\prod_i P(D_i)$.

The minimization of $-\log L$ then yields the optimal values of E, X_{max}, N_μ as well as the shower axis direction and the core position and time at which the shower impacts the ground. Minimization in such a large parameter space is time consuming, but our early studies of this procedure have yielded promising results. In a Monte Carlo study, we simulate the signal distributions for the Pierre Auger surface detector array configuration for 50EeV showers at θ=45 with the X_{max} and N_μ sampled from distributions obtained from iron/QGSJET01 shower simulations. To reconstruct the showers, we first sample the initial guesses of energy and core position from error distributions with $\Delta E/E$=30%, Δx_{core}=30m. For simplicity, the shower axis direction is fixed to its true value. We then divide each detector signal trace into three bins in time: a pre-trigger bin, a bin containing the first 50% of the time-integrated signal, and a bin containing the remainder of the signal. The corresponding bins in S and F are recreated in the fit for each call to L. After fitting, we find statistical and systematic errors of 14% and -17% in energy, 38g/cm^2 and +14g/cm^2 in X_{max}, and 25% and +20% in N_μ. The resolutions worsen at very small or very large zenith angles as the asymmetries disappear and the parameters become more degenerate.

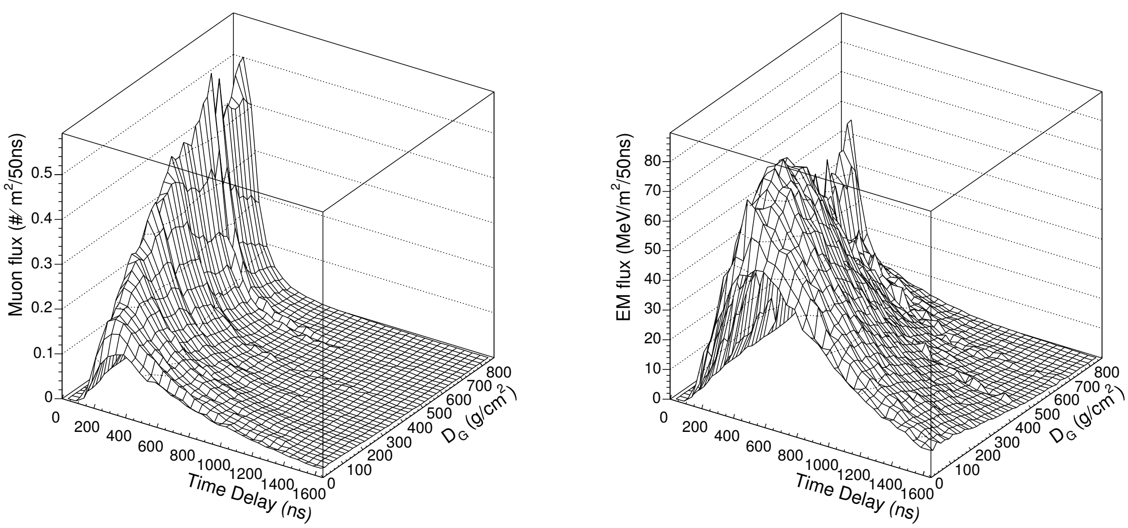

Figure 2. (Left) The muon number flux plotted versus time and D_G. This distribution can be multiplied by ~240MeV/muon to obtain the corresponding signal flux. (Right) The EM energy flux plotted versus time and D_G. Note the sharp peak due to the muon decay halo. Both figures use R=900m, ζ=0, E=10EeV proton/QGSJET01 simulations.

References

[1] A. Chou et al., 29th ICRC, Pune (2005) usa-chou-A-abs1-he14-poster.
[2] P. Billoir, Pierre Auger Observatory Internal Note, GAP 2000-025.