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Simulation study of shower profiles from ultra-high energy cosmic rays

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Abstract: The identification of the primary particle type can provide important clues about the origin of ultra-high energy (UHE) cosmic rays above 10^{18} eV. The depth of shower maximum of the air shower profile offers a good discrimination between different primaries. This observable is usually extracted from a fit to the longitudinal shower profile. Recently it has been used to obtain a limit to photons from data taken by the Pierre Auger Observatory. In this paper we study the fit quality that is obtained with different functional forms for simulated shower profiles of nuclear and photon primaries. The impact of the functional form on the extrapolation to non-observed parts of the profile is commented on. We also investigate to what extent additional profile parameters such as the width of the profile or a reconstructed "first interaction" of the cascade can be exploited to improve the discrimination between the primaries.

Introduction

Determining the composition of the UHE cosmic rays above the knee region is one of the challenges in cosmic rays detection. In particular the Fluorescence Detector of the Pierre Auger Observatory is observing directly the longitudinal shower development in the atmosphere. The detected light intensity, including the Fluorescence and Cherenkov direct and scattered contributions, and taking into account the atmospheric effects, is proportional to the energy deposited at each depth.
The so called longitudinal shower profile, in shower size or energy deposit, as a function of atmospheric slant depth can be reconstructed with good accuracy and the non-observed part extrapolated. As a matter of fact the shower profile can be well described by a trial function (GH) originally proposed by Gaisser and Hillas [1]:

$$\begin{aligned} GH(X) &= \left.\frac{dE}{dX}\right|_{X_{max}} \left(\frac{X-X_0}{X_{max}-X_0}\right)^{\frac{(X_{max}-X_0)}{\lambda}} \\ &\cdot \exp\frac{(X_{max}-X)}{\lambda} \end{aligned} \tag{1}$$

where X_{max} is the position of shower maximum in slant depth, $\left.\frac{dE}{dX}\right|_{X_{max}}$ is the energy deposit at shower maximum.

X_0 and λ are strongly correlated and connected with the starting point and width of the curve, but cannot directly be interpreted as the first interaction point and interaction length, as already pointed out in [2].
The observable X_{max} has good discriminating power between the different primaries inducing the cascade. The average value of the simulated distribution for photons differs from that of hadrons by about 200 gcm^{-2} at 10 EeV.
This evidence was used to set a limit to the the photon fraction of the total flux [3] and for a recent update see [4].

Composition sensitivity of profile shape

The motivation of this study is to search for further sensitive observables to enhance the discrimination power between different primaries (for an independent analysis see [5]). Photon selection, for instance, could be contaminated by late developing hadron cascades, in particular from deeply fluctuating protons.
In Fig. 1 the energy deposit as a function of slant depth for some example profiles is plotted (dashed blue line for photons, thick red line for protons). The protons have been chosen to have a deep value

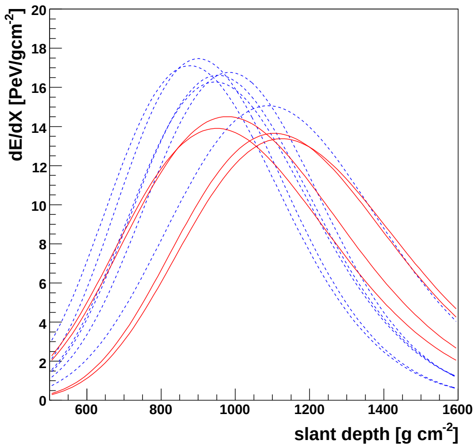

Figure 1: Example of $\frac{dE}{dX}$ profiles of simulated showers induced by photons (dashed blue line) and protons (thick red line) at 10 EeV.

of the shower maximum, compatible with the photon average distribution.

A dedicated study has been performed on a set of simulated CORSIKA [6] showers induced by different primary particles. The sample consists of 750 protons, 500 iron nuclei, and 800 photons at an energy of 10 EeV (FLUKA [7] and QGSJET1 [8] as low and high-energy hadronic interaction models). The possibility to exploit the information of the profile shape, like for instance the width, has been investigated.

Other proposed trial functions, like a gaussian [9, 10] and double gaussian [11] in shower age, have been included in the fitting routine and tested on the same set of simulated events. Finally, a detailed study on the parameters correlations and the Principal Component Analysis (PCA) have been performed. Results are presented in the following sections.

CORSIKA profile and Gaisser-Hillas fit

The longitudinal profile of each event is recorded in the CORSIKA output file, together with the result of a 6-parameter Gaisser-Hillas fit. Here λ, see Eq. 1, is replaced by a quadratic function of the atmospheric depth.

This fit is found to be robust for deriving X_{max} but less efficient in adapting the shape of the GH curve to data points. This may be connected with the limited number of profile points, especially in the falling side of the shower development.

A more effective 4-parameters constrained fit with the GH function has been implemented as in [12]. The X_{max} value agrees to CORSIKA better than 1 gcm^{-2}. In Tab. 1 the average slant X_{max} and the RMS values of the distribution for iron, proton and photon showers are summarised. The average X_{max} value for photons differs from that of hadrons by $\sim$ 200 gcm^{-2}.

Table 1: Mean and RMS of the X_{max} distribution for the simulated primaries at 10 EeV, 4-parameters GH fit.

	$< X_{max} >$ [g cm^{-2}]	RMS [g cm^{-2}]
Iron	695	22
Proton	780	67
Photon	969	59

Other trial functions and PCA analysis

The longitudinal profile can be translated into shower age s by means of the following transformation:

$$s\,(X) = \frac{3X}{X + 2X_{max}} \qquad (2)$$

that aligns the profiles at $s(X_{max}) = 1$ and is scale-free. The shower starting point is in this case set to 0, but it could be added as a fourth fit parameter by substituting X with (X-X_1). The normalised profile can be then fitted by the following gaussian function in age (AG):

$$AG\,(s) = \exp\left(-\frac{1}{2\sigma^2}(s-1)^2\right) \qquad (3)$$

where σ and X_{max} are free parameters, together with $\frac{dE}{dX}\Big|_{X_{max}}$.

Following [11] we can employ a double gaussian (2G) with two different widths corresponding to the shower development before and after the shower maximum. The number of free parameters is increased in this case to four.

In Fig. 2 the average relative residuals, as a function of shower age, obtained with the tested analytical fit functions are plotted for the proton sample. In Tab. 2 the mean and RMS values of the σ of the gaussian for the simulated iron, proton and photon showers are summarised. The correlation between the width of the gaussian AG and the depth of shower maximum is shown in Fig. 3. A later development of the cascade is associated with a narrower profile width. Similar average values and the same correlation are found between the rising edge σ and the X_{max} for the 2G fit, in agreement with the previously cited works.

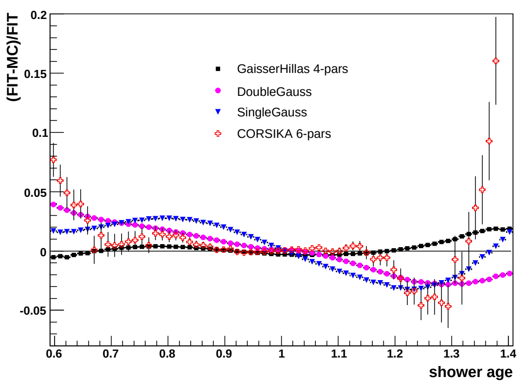

Figure 2: Average relative residuals to the tested analytical functions for protons at 10 EeV: GH 4-parameters fit (black squares), single gaussian (blue triangles), double gaussian (pink bullets), and 6-parameters CORSIKA (red crosses).

Using X_1 as a free parameter in the fitting process we observe a correlation with σ that can be represented, both for hadrons and photons, by a straight line. This correlation is shown in Fig. 4 for the simulated sets of iron, proton and photon

Table 2: Mean and RMS values of the σ distributions for the simulated primaries at 10 EeV.

	$<\sigma>$ [g cm^{-2}]	RMS [g cm^{-2}]
Iron	0.22	0.006
Proton	0.20	0.015
Photon	0.16	0.011

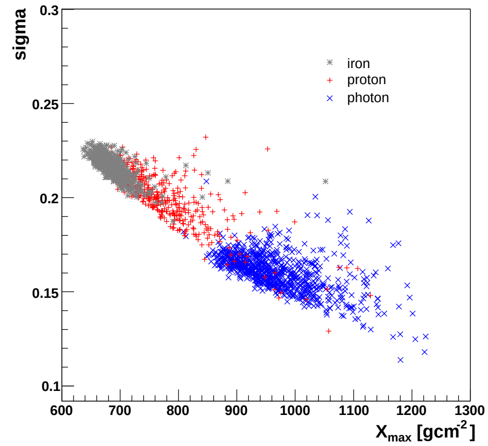

Figure 3: Correlation between the width of the gaussian (AG) and depth of shower maximum for showers initiated by iron, proton and photon primaries, respectively marked as grey stars, red crosses and blue $\times$-shaped crosses.

primaries, respectively marked by grey stars, red crosses and blue $\times$-shaped crosses.

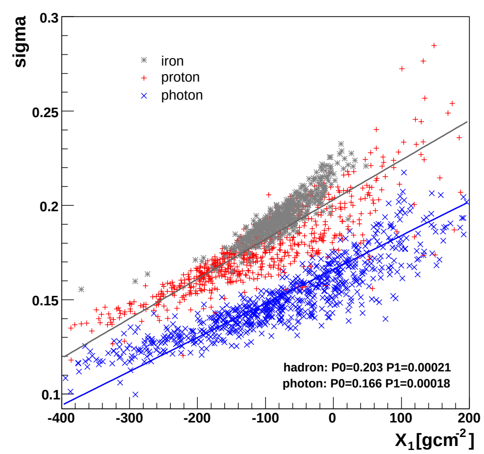

Figure 4: Correlation between σ and X_1 for the gaussian fit, same color code as Fig. 3.

The possibility to exploit the additional information carried by the width of the profile, described by σ, for the separation between different pri-

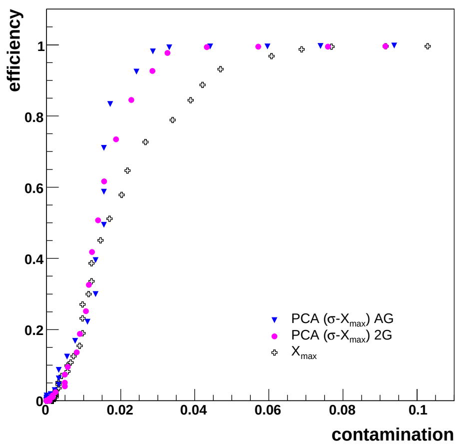

Figure 5: Efficiency for accepting photons as a function of hadron contamination in the PCA-transformed variable (σ and X_{max} combined) for the single gaussian (blue triangles) and for the double gaussian (pink bullets) compared to the X_{max} cut (black crosses for AG).

maries has been studied. Applying the Principal Component Analysis (PCA) it has been quantified fot the case of photon-hadron separation.
In Fig. 5 the efficiency of a cut for accepted photons in the PCA transformed variable is plotted as a function of the hadron contamination. Blue triangles refer to the single gaussian fit and pink bullets to the double gaussian fit. The photon-hadron separation power of a cut in the PCA variable compared to a X_{max} cut on the data set (black crosses for the AG) is clearly enhanced in both cases. Other PCA tests, on the variables from the GH and gaussian fits, gave less evident results.

Conclusions

We have verified that the depth of shower maximum, X_{max}, has a very good discriminating power between cosmic rays primary particles. The quality of the different fitting functions and the correlation between the fit free parameters have been checked.
The possibility to exploit further information, as for instance the width of the shower profile or the shower starting point, has been investigated. The hadron-photon separation power of a simple X_{max} cut has been quantified and compared to the one achievable combining other sensitive observables. An enhancement of the photon-hadron separation power is found for both studied profile descriptions (gaussian and double gaussion in shower age). The PCA shows that the best cut is the one that combines X_{max} with the single gaussian σ.
Other PCA tests, e.g. adding another variable from the GH or gaussian fits, gave less evident results. Further tests on those observable are planned especially for the Pierre Auger Fluorescence Detector including its full detector simulation.

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