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

V. Scherini[(1)], F. Schüssler[(2)], R. Engel[(2)], K.-H. Kampert[(1)], M. Risse[(1)], M. Unger[(2)]

[(1)]University of Wuppertal, Germany [(2)]Forschungszentrum Karlsruhe, Germany

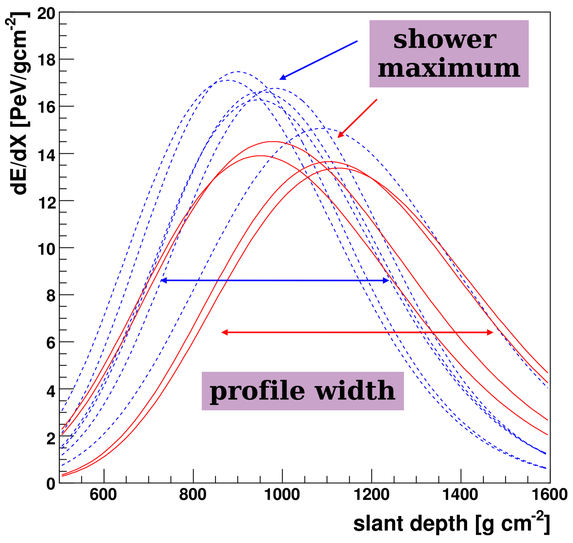
Bergische Universität Wuppertal

Forschungs-Zentrum Karlsruhe

Outline:

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. In this paper we study the fit quality that is obtained with different functional forms for simulated shower profiles of nuclear and photon primaries. 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.

Composition sensitivity of profile parameters



Examples of dE/dx profiles for 10^{19} eV primaries: blue dashed for photons, red solid lines for deep protons. Protons with a X_{max} compatible with photon average simulated distribution have been chosen

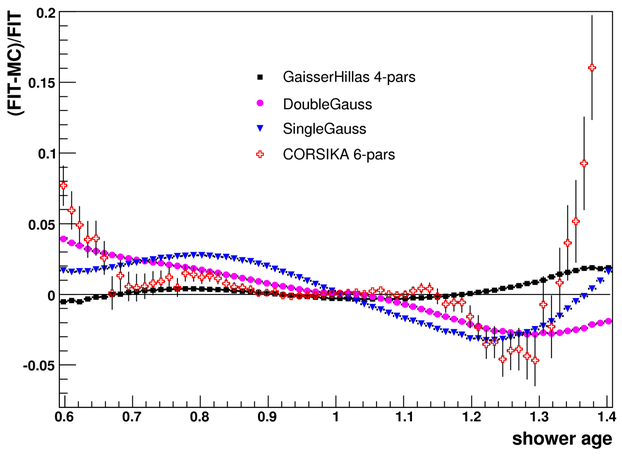
X_{max} has good mass discriminating power. Its average value for photons differs from that of hadrons by about 200 gcm^{-2} at 10^{19} eV. This evidence was used to set a limit to the the photon fraction of the total cosmic ray flux.

Auger Collaboration, these proc. #602

Comparing different functional forms

The 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 from a fit:

- 6 parameters Gaisser-Hillas (CORSIKA)
- 4 parameters constrained **GH** M. Unger et al., these proc., #972
- gaussian in shower age (**AG**) **-> HIRES coll., Astrop.Phys., 14 (2000) 7-13**
- double gaussian (**2G**) **-> M. Giller et al., J. Ph. G, 31 (2005) 947-958**



Average relative residuals to the tested analytical functions at 10 EeV for the proton sample.

The simulation sample

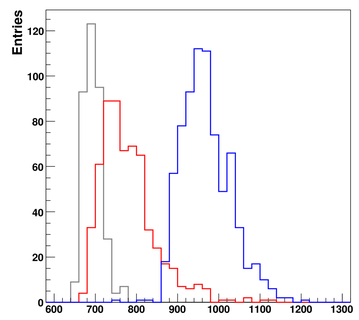
A dedicated study has been performed on a set of CORSIKA [1] showers at **energy 10^{19} eV,** distributed zenith angles. (hadronic interaction models FLUKA [2] , QGSJET-II [3])
500 **iron** nuclei, 750 **protons**, 800 **photons**

[1] D. Heck et al. Report FZKA **6019** (1998)
[2] A. Fasso et al.,CERN-2005-10, INFN/TC 05/11, SLAC-R-773
[3] N. N. Kalmykov and S. S. Ostapchenko. Phys. of At. Nucl., **56** (1993) 346–353

Gaisser-Hillas function

$$GH(X) = \frac{dE}{dX}\Big|_{X_{max}} \left(\frac{X - X_0}{X_{max} - X_0}\right)^{\left(\frac{X_{max}-X_0}{\lambda}\right)} \cdot \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

X_{max} distribution



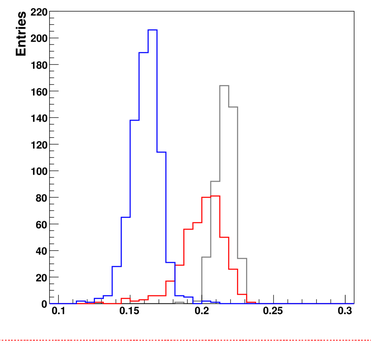
	<Xmax>	RMS
Iron	695	22
Proton	780	67
Photon	969	59

gaussian in shower age

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

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

σ distribution

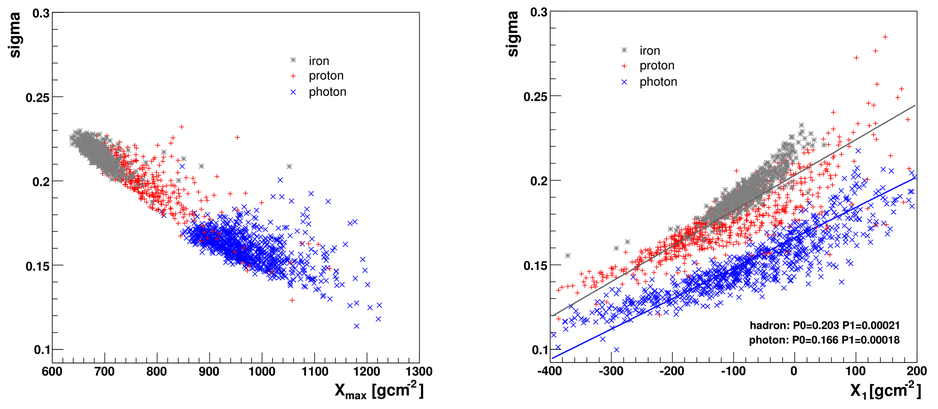


	<σ>	RMS
Iron	0.22	0.006
Proton	0.20	0.015
Photon	0.16	0.011

The fitting routines describe accurately the profile shape, in particular around the shower maximum. The GH 6-parameters fit is weaker at the curve extremes especially at the falling side of the curve. The 4-parameters constrained GH is found to be robust and efficient.

Enhancement of the hadron-photon separation power

Correlations between fit parameters

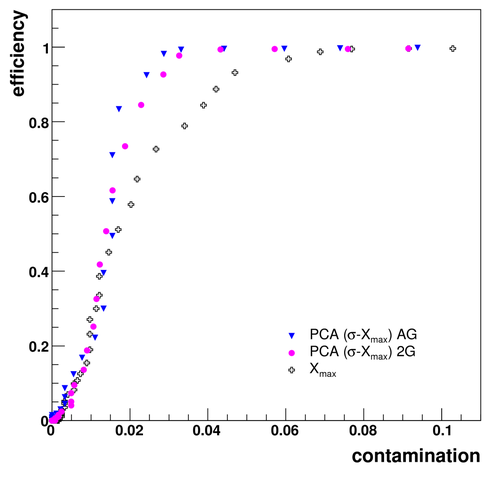


Left: correlation between the width of the gaussian (AG) and depth of shower maximum; **right**: correlation between the width of the gaussian (AG) and curve starting point X_1. Showers initiated by iron, proton and photon primaries, marked as grey stars, red crosses and blue x-shaped crosses, respectively.

A later development of the cascade is associated with a narrower profile. 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.
Using X_1 as a free parameter in the AG fit we observe a correlation with σ that can be represented, both for hadrons and photons, by a straight line.

Principal Component Analysis on combined variables

The possibility to exploit the additional information contained in the shower profile, for instance the width or the curve starting point, has been studied applying the PCA to the simulated data sets.



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}-only cut (black open crosses).

The efficiency of a cut for accepted photons in the PCA transformed variable is plotted here 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 is compared to a X_{max}-only cut on the data set (black open crosses).
The same test on the combined variables from the Gaisser-Hillas 4-paramenters fit did not improve the separation.

The PCA shows a **clear enhancement** of the photon-hadron separation power comparing to a cut based on depth of shower maximum only.
The best results are achieved combining the width of the gaussian σ and X_{max} for the case of the single gaussian fit (AG).

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