EAS transverse profiles in the $X_{\max}$ region at energies of $10^{14} - 10^{17}$ eV

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***Abstract*— The transverse profiles of Extensive Air Showers in the region of $X_{\max}$ and its dependence with the composition of the primary particle is studied in this work. Simulations using Corsika shows, for energies in the range $10^{14} - 10^{17}$ eV, a sizeable difference in the shape of the transverse profile for EAS initiated by Proton or by Iron. However this differences smooths out with increasing energies.**

I. Introduction

The determination of the composition of high energy cosmic rays has been the subject of an enormous interest and of many controversies. It is, no doubt, a very difficult experimental measurement as it relies on the observation of small effects on the development of the Extended Airs Showers (EAS) and on its comparison with reference Monte Carlo simulations which depend on several not-well known parameters.

The fluorescence technique allowing a space reconstruction of the EAS, have, in this context, a high potentiality. In fact, several fluorescence experiments have measured the distribution of the shower maxima, $\mathrm{X}_{\max}$, which has been extensively shown to be sensitive to the composition of the high energy cosmic rays. However, $\mathrm{X}_{\max}$ can never, even in an experiment with an ideal resolution, be used in an event by event basis. The size of the statistical fluctuations in $\mathrm{X}_{\max}$ in each event, due for instances to the fluctuation in the position of the first interaction, X_0, are of the same order of magnitude of the mean difference between the expected $\mathrm{X}_{\max}$ for EAS initiated by protons or by iron nuclei $\left(\sim 70\,\mathrm{g}\cdot\mathrm{cm}^{-2}\right)$. On the contrary, it is argued in this paper that, in the energy range from 10^{14}eV to 10^{17} eV, an ideal measurement of the transverse profile in the $\mathrm{X}_{\max}$ region could be used, in a non ambiguous way, to identify the composition of each event.

The transverse momentum distributions of the secondaries produced in an iron-air collision and in a proton-air collision are not substantially different. However, if the primary is the same, the mean energy per nucleon is, in the case of an iron collision much smaller ($\sim 1/56$) than in the case of a proton collision. This fact is translated into smaller opening angles of the secondaries for proton initiated air showers and thus into narrower transverse distributions, at least in the central region of the air showers where the hadronic component is stronger. Statistical fluctuation must be small as the multiplicity at high energy proton-air collisions is already of the order of several tens of particles.

TABLE I

Caracteristics of generated samples. For each Energy two samples were generated with different primaries (proton and iron) using the QGSJET hadronic interaction model.

E	nº events	thin	Wlim	Radial thin
10^5 GeV	100	0	10^4	$1.5 \cdot 10^2$
10^6 GeV	10	10^{-6}	10	$1.5 \cdot 10^2$
10^7 GeV	10	10^{-6}	10^2	$1.5 \cdot 10^2$
10^8 GeV	10	10^{-6}	10^3	$1.5 \cdot 10^2$

II. Transverse profiles at Xmax

The detailed development of an EAS is usually modeled by Monte Carlo simulation programs which aim to follow, as much as possible, the production, transport and interactions of each individual shower particle. This scheme is constrained both by the uncertainties on the knowledge on the interaction of the particles on matter, particularly from the hadronic part, and on, the always limited, computing power. Anyhow the progress made in recent years in both directions made possible to describe in a consistent way experimental results over a wide range of energies on a level of 10 to 20% [1], [2].

In the present paper the CORSIKA[3] simulation package, which is the reference in the field, is used to produce samples of EAS initiated either by protons or by iron nuclei in an energy range between 10^{14} and 10^{17} eV. For each Energy two samples were generated with different primaries (proton and iron) using the QGSJET hadronic interaction model. For energies above 10^{15} eV the thinning option was used setting the thinning parameter $\varepsilon_{\mathrm{th}} = 10^{-6}$ and applying a weight limit $W_{\mathrm{lim}} = E_{\mathrm{prim}} \cdot \varepsilon_{\mathrm{th}}$, where E_{prim} is the primary energy in GeV. These choices ensure that the fluctuations introduced on the e^+e^- lateral distributions by the thinning are of the order of just a few % for distances to the shower axis below $1000\,\mathrm{m}$. Table I summarizes the characteristics of the generated samples. The output of each generated event contains information on its longitudinal profile as well as on several transverse profiles at chosen observation levels placed along the shower axis. Table II summarizes the depths of the chosen observation levels.

The lateral profiles near the shower maximum for a proton (solid blue) and an iron (dashed red) event with energy $E = 10^{15}$ eV are shown in fig. 1 . This image confirms that the proton lateral distributions are, in the central region, sharper

TABLE II
DEPTHS OF THE CHOSEN OBSERVATION LEVELS.

Observation level	depth $\left(\mathrm{g/cm^2}\right)$
1	100
2	200
3	300
4	400
5	500
6	600
7	700
8	800
9	900
10	1000

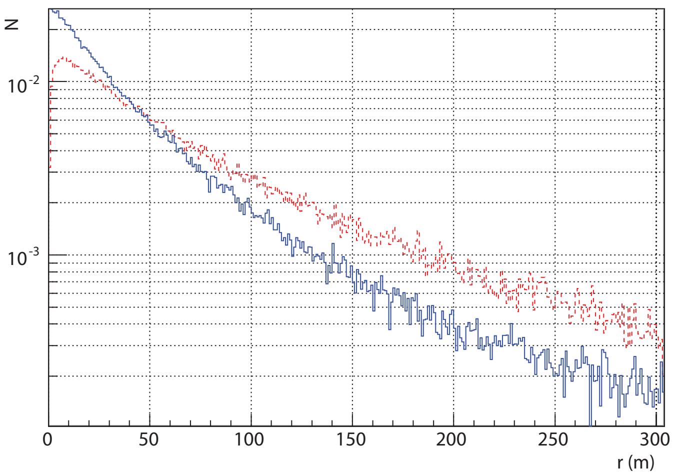

Fig. 1. Comparison of lateral profiles for a proton (solid blue) and an iron (dashed red) event with energy $E = 10^{15}$ eV near the shower maximum.

than the corresponding distributions for iron.

In fig. 2 and 3 the longitudinal profile of respectively one proton and one iron event with an energy $E = 10^{15}$ eV are shown as an example. In the same figures the contributions for the longitudinal profile from the particles with a transverse distance to the shower axis below and above $R_{\mathrm{cut}} = 50$ m are also shown. It is striking that the ratio between these two contributions is well above 1 in the case of the proton EAS while it is of the order of 1 in the case of the iron EAS. In order to quantify this effect we define the variable

$$\mathrm{Rat} = N_{\mathrm{central}}/N_{\mathrm{total}}$$

with

$$N_{\mathrm{central}} = \int_{X_{\mathrm{max}}-\delta}^{X_{\mathrm{max}}+\delta} \int_{0}^{R_{\mathrm{cut}}} \rho\left(r,t\right) dr dt$$

$$N_{\mathrm{total}} = \int_{X_{\mathrm{max}}-\delta}^{X_{\mathrm{max}}+\delta} \int_{0}^{\infty} \rho\left(r,t\right) dr dt$$

where $\delta = 100\,\mathrm{g\cdot cm^{-2}}$ and $\rho\left(r,t\right)$ is the particle density at a given distance r from the shower axis for a given depth t.

Fig. 4 and fig. 5 show the distributions of $\mathrm{Rat_{proton}}$ (solid blue) and $\mathrm{Rat_{iron}}$ (dashed red) for energies of $E = 10^{14}$ eV

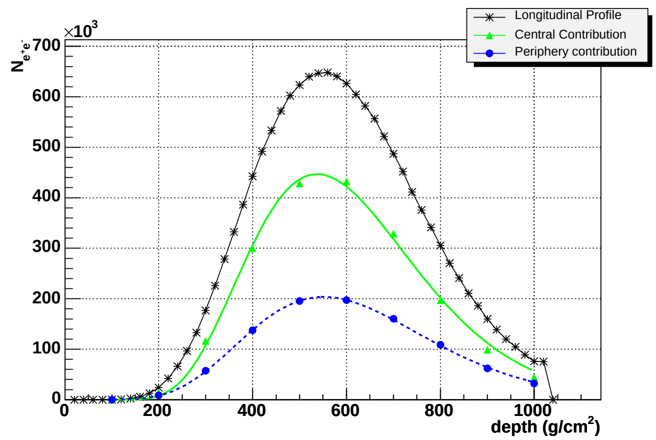

Fig. 2. Longitudinal profile of a proton event with energy $E = 10^{15}$ eV.

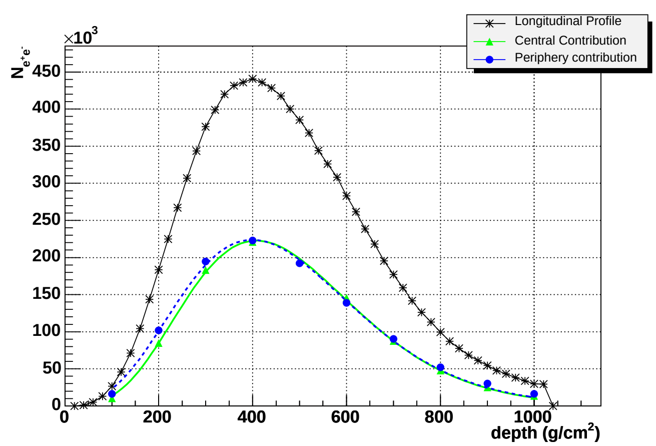

Fig. 3. Longitudinal profile of an iron event with energy $E = 10^{15}$ eV.

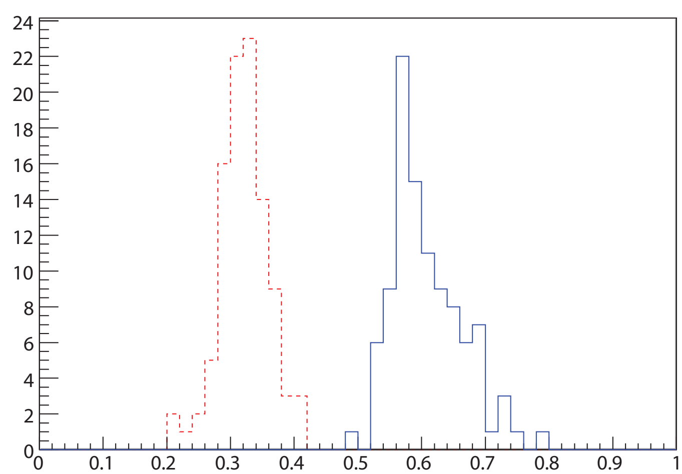

Fig. 4. Rat distributions for proton (solid blue) and iron (dashed red) EAS generated with an Energy of $E = 10^{14}$ eV

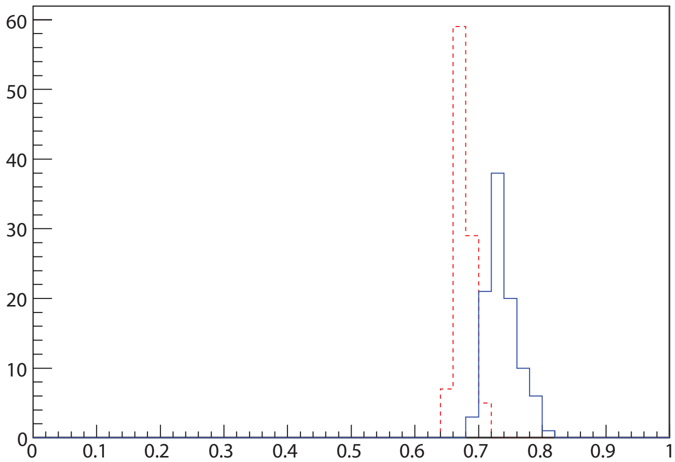

Fig. 5. Rat distributions for proton (solid blue) and iron (dashed red) EAS generated with an Energy of $E = 10^{17}$ eV

and $E = 10^{17}$ eV, respectively. These Rat distributions were computed over two generated samples of proton and iron EAS, with $R_{\mathrm{cut}} = 50\,\mathrm{m}$. Fig. 4 shows a clear separation between the Rat distributions for proton and iron initiated EAS. For higher energies the fluctuations in Rat tend to decrease, which is reflected on the width of the distribution as can be seen in fig. 5. It can also be seen that the difference between the proton and iron distributions tend to vanish with the increase of the energy.

III. Conclusion

We have shown in this work that the shape of the lateral distribution of particles in a Extensive Air Shower, in the range of Energy $10^{14} - 10^{17}$eV, depends on the primary that initiated the EAS. It is shown that the lateral profile of a proton initiated EAS has a steeper dependence with the distance from the core than an iron initiated EAS. It was then possible to analyse the number of particles in the core (<50m) versus the total number of particle and conclude that such a variable could be used to study the EAS composition in this energy range if one has access to precise measurements of the lateral profiles near the shower maximum. It was also shown that the discrimination power of such variable tends to decrease with the increase on the energy. It is also necessary to consider that a non ideal detector will spoil the RAT distribution and make it possible only for low energies were the RAT distributions are well separated.

It has been shown in [4] that for energies above $E = 10^{19}$eV a composition independent lateral distribution function can be assumed. Thus, for these energies the lateral profile cannot be used to discriminate a proton from an iron initiated EAS, even with an ideal detector.

References

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